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PREFACE

This is Number 1 of Volume 48 of the Quarterly TRANSACTIONS of the A. I. E. E. It consists of the papers and discussions from the 1928 Pacific Coast Convention (Spokane, Washington) and the Regional Meeting of the Southern District (Atlanta, Georgia).

In addition to the papers at the above meetings, two papers, *Radio Acoustic Finding in Hydrography*, by Mr. Jerry H. Service, and *The Calculation of the Capacitance between Two Wires of a Three-Conductor Cable*, by Mr. Y. W. Lee, are included in this number.

For convenient reference, an index of authors and discussors has been included in this number.

Sphere-Gap and Point-Gap Arc-Over Voltage

As Determined by Direct Measurement

BY JOSEPH S. CARROLL[1] and BRADLEY COZZENS[2]
Associate, A. I. E. E. Associate, A. I. E. E.

Synopsis.—This is a report of some of the work done at the Ryan High Voltage Laboratory, Stanford University, during the school year of 1927-28. A new method of measuring high voltages is described, in which the current through a water resistor is recorded on an oscillograph. Over a million volts to ground was measured with an accuracy believed to be better than 2 per cent.

A calibration of the meter sphere gap was determined for voltages up to 1100 kv. and the arc-over voltages for point gaps were determined for distances up to 30 ft. Point to plane arc-over voltages were also measured.

Included in the report are some tests made in connection with the shielding of the water resistor determining to what extent capacity currents were causing error.

Sphere gaps were also used in connection with the determination of the arc-over voltages of the point gaps to determine whether there was any high frequency, set up by the heavy corona streamers from the point, that could not be recorded by the oscillograph.

The procedure of taking an oscillogram of the corona current from a pointed electrode a million volts above ground is described.

The practicability of the use of the meter sphere gap for voltage measurement is discussed.

* * * * *

INTRODUCTION

At the time of this investigation, the methods of direct high voltage measurement (for voltages in excess of 200 kv.) were limited to the sphere gap, point gap, dividing condenser as used with electrometer or cathode ray tube, and direct measurement of the current flow in a condenser of known capacity. The latter method had been used as a basis for the calibration of the sphere gap of 50-cm. spheres for voltages up to 500 kv.[3] The calibration of the 100-cm. sphere gap was for the most part theoretical, based on electrostatics and values determined on spheres of a lesser diameter.[4] The values of arc-over voltage for points gap for voltages in excess of 900 kv. was a matter of extrapolation of sphere gap comparison. Neither the sphere gap of 100-cm. spheres nor the points gap had been calibrated by a direct method of voltage measurement for voltages in excess of 550 kv. It was known by those familiar with the use of these gaps that their action was not positively established. The object of this investigation was thus to establish the calibration for the meter sphere gap and points gap for the higher voltages, based upon values obtained by direct measurement within a limit of error of 2 per cent.

METHOD OF VOLTAGE MEASUREMENT

In the absolute measurement of high voltage it is necessary to use fundamental methods. One of the simplest is that involving Ohm's Law, in which the voltage is given by determining the current flowing through a known resistance. The question then arises as to the availability of a resistance that can be connected to a million-volt circuit. The value of the resistance is determined by the amount of current that is required in the measuring circuit. This can only be determined after the kind of meter has been chosen.

In order to choose the meter it is necessary to decide in what terms the voltage will be required: average, effective, or crest value. In high voltage measurements one is concerned largely with arc-over voltages and since arc-overs are dependent to a considerable degree upon crest value, it is necessary to know either the crest value or the wave form. The latter is usually as much of an unknown as the magnitude of the voltage. Therefore, it is a logical procedure to record the current through the high resistance on an ordinary oscillograph, which tells all that it is necessary to know about the voltage wave. This then fixes the current value, for reasonable accuracy in measurement, somewhere between 20 milliamperes and 100 milliamperes. For practically all of the measurements reported in this paper, a current of 50 milliamperes was used. With 50 milliamperes and one million volts a 20-megohm resistor is required capable of dissipating 50 kw. if operated continuously. At this point the question arises as to the necessity for continuous operation when the oscillograph is used. If the voltage can be raised in the proper manner for the test and the oscillograph cut in at the instant the voltage is to be determined and then the voltage turned off the resistance, continuous operation is not necessary. A glass tube filled with distilled water makes a suitable resistor when operated in the above manner. The length of the tube must be great enough so that the applied voltage will not arc it over from end to end, and the tube must have a diameter such that there is sufficient water to prevent excessive rise in temperature during the application of the voltage. Fortunately the specific heat of water is high. For all of the work involving the use of the water resistor, the voltage was raised from zero to full value

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[3] L. W. Chubb and C. Fortescue, *Calibration of the Sphere Gap Voltmeter*, A. I. E. E., Vol. XXXII, 1913, p. 739.

[4] F. W. Peek, "Dielectric Phenomena," McGraw-Hill Book Co.

Presented at the Pacific Coast Convention of the A. I. E. E., Spokane, Wash., Aug. 28-31, 1928.

28-128

in one second. This is where a motor generator set as a source of power adapts itself very well to such work.

Change in Resistance as a Result of Heating. The voltage is applied to the test specimen by first closing in the main generator oil switch connecting the transformer set to the generator bus. Then with the correct voltage on the generator exciter, the generator field switch is closed in. The voltage is thus built up rapidly without surges. The heat that is generated in the water resistor during the one second that the voltage is building up based on a uniform rise in voltage from zero to 1000 kv.[5] (effective value) may be determined as follows:

Let H = amount of heat in calories
R = resistance of the resistor
I = current through the resistor
K = gram calories per watt sec. = 0.24

$$k = \frac{\text{Final amps.}}{\text{Total time}} = \frac{0.05}{1} = 0.05$$

$$dH = K\, I^2\, R\, dt$$

$$I = k\, t$$

$$dH = K\, k^2\, t^2\, R\, d\,t$$

$$H = K\, k^2\, R \int_{t=0}^{t=1} t^2\, d\,t$$

$$H = \frac{K\, k^2\, R\, t^3}{3}$$

$$H = \frac{0.24 \times 0.05^2 \times 20 \times 10^6 \times 1}{3} = 4000$$

calories

The diameter of the glass tube used was 0.4 in. and the length was 16 ft. The tube was in three sections coupled with rubber tubing. The tube contains 383 cu. cm. of water, the temperature of which would be raised approximately 10 deg. cent. This rise in temperature causes a decrease in resistance which must not be overlooked. The approximate change in resistance can be determined from the formula:[6]

$$R_t = \frac{40 \times R_{20}}{20 + t}$$

t = Temperature deg. cent.
R_t = Res. at any temp. between 0 deg. and 100 deg. cent.
R_{20} = Res. at 20 deg. cent.

In the work herein described this change in resistance was seldom greater than 15 per cent. This decrease in resistance due to a change in temperature requires that the resistance measurement of the water resistor be made immediately after the oscillogram is obtained.

Operations Necessary for Voltage Measurement. The actual procedure for the measurement of arc-over voltage may be followed from Fig. 1. First the generator oil switch and main generator field switch are closed in. The cam operated contactor is then started which first closes contact A closing the Magnetic Switch and shorting out all of the external resistance in the generator field. The voltage of the set is thus built up with the increase in generator field current and after approximately one second the oscillograph shutter is opened by the closing of contact B. However, just before this takes place the closing of contact C boosts the voltage on the incandescent light used in the oscillograph. The voltage of the generator exciter is set by trial so that arc-over occurs sometime within ten cycles after the shutter is opened. A quick acting relay R_1 closes the shutter in less than two cycles after arc-over. The generator oil switch is opened in six cycles by the action of the overload relays. Immediately after the arc-over, the disconnects are opened preparatory to determining the resistance of the water tube resistor.

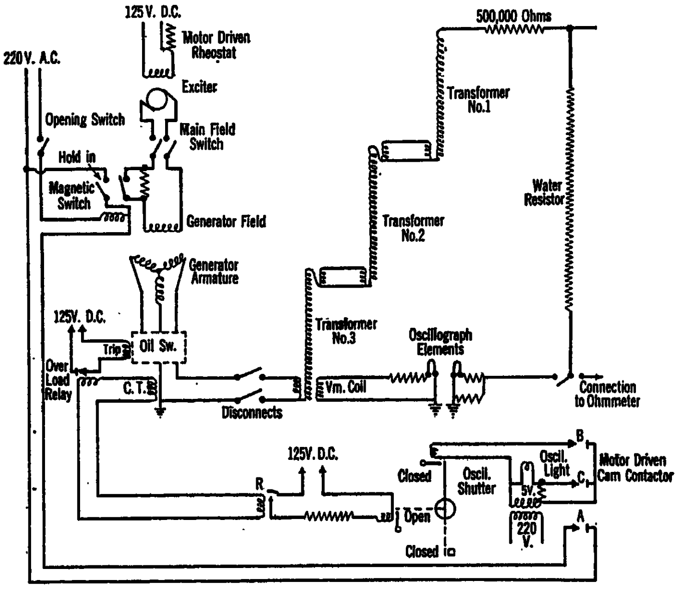

FIG. 1—SIMPLIFIED DIAGRAM OF MAIN CIRCUIT

Method of Resistance Measurement. The resistance of the column can be determined within 20 seconds after arc-over. The slight radiation occurring in this time is negligible and is similar in magnitude to the additional heating caused by the voltage impressed during arc-over. Due to the high resistance used in the high voltage leads, the potential impressed upon the water resistor is small during arc-over, being less than one per cent of the voltage before arc-over. To measure the resistance of the water resistor, the switch S_1, Fig. 2, is thrown from position a to position b changing the water resistor connection from the oscillograph element to the high potential side of a 1000-volt d-c circuit. In position b the other contact of S_1 closes the 1000-volt circuit by operating a magnetic switch. Switch S_2 is thrown to position b connecting the galvanometer to a flexible lead which had been connected to the top of the water column. The galvanometer deflection is then read. Switch S_2 is then thrown to position *a* which connects the galvanometer in a circuit to which the 1000 volts is applied and having a known equivalent resistance approximately equal to the resistance of the water resistor. The galvanometer reading for this connection is also obtained. The resistance of the water resistor is then determined by the relation (Gal. Def. with Equiv. Res.)/(Gal. Def. with Water Res.) × Equiv. Res. = resistance of water resistor. Following each arc-over, sufficient water is drained from the glass tube so that all of the heated water is replaced by fresh cool water from the gallon glass contained at the top.

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[5] This will vary somewhat from a straight line relation depending upon the degree of saturation of the generator field one second after the voltage is applied.

[6] From tests by Applequest and McKenny, M. I. T. 1912. Pender Handbook (Edition 1922), p. 1356.

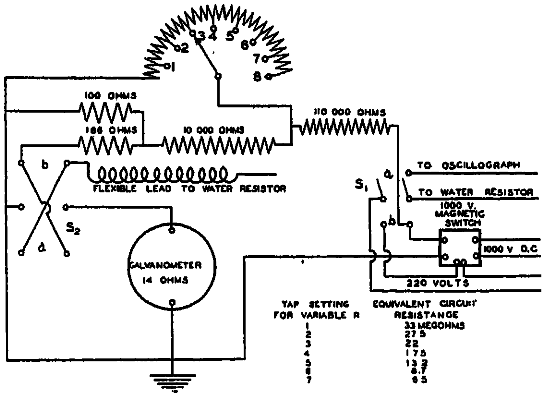

FIG. 2—CIRCUIT DIAGRAM FOR OHMETER

Method of Oscillograph Calibration. The oscillograph element is calibrated by recording on the same film on which the record is taken, a current from the sine wave generator having approximately the same crest as the current through the water resistor. The effective value of this current is read on a milliammeter. Fig. 3 is a half section of film showing three of five records taken on the same film and also the calibration for this set of records. Each record contains two waves; one is the current through the water resistor and the other is the voltage as given by the voltmeter coil of the grounded transformer. The amplitude of the cycle preceding arc-over is the value used in the determination of the arc-over voltage. The total amplitude of the record (from positive crest to negative crest) is measured in all cases, being of the order of three inches. The ratio of the amplitude of the record to the amplitude of the calibrating wave multiplied by the effective value of the sine wave current used in calibration is the effective value of a sine wave current having the same crest as the current through the water resistor. This current value multiplied by the determined resistance of the water resistor is the total effective (sine wave equivalent) voltage computed from crest values.

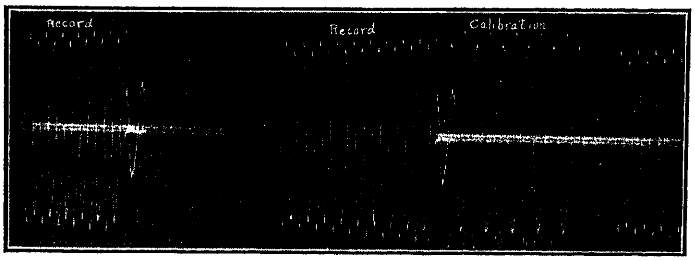

FIG. 2—TYPICAL OSCILLOGRAM AS OBTAINED FOR VOLTAGE DETERMINATION

TESTS AND DETERMINATIONS

During tests at the Ryan High Voltage Laboratory, it had been observed that at the time of arc-over of a 20-foot gap between points, the voltmeter coil in the ground unit of the chain connected set of six transformers indicated an effective value of terminal voltage 33 per cent less than that which was expected for the gap breakdown, based on the assumption that the value of 10 kv. per inch for points gaps at short separations was approximately correct for the longer gap lengths. It has been assumed previously in the explanation for the low voltmeter coil value for arc-over voltage, that the heavy corona streamers accompanying the breakdown of the gap caused high frequency or surges to be superimposed on the 60-cycle voltage. However, the oscillograms showed that the arc-over of the 20-foot gap was purely a 60-cycle breakdown and that the crest value of the voltmeter coil value of terminal voltage was but slightly different from that as determined by the water resistor and oscillograph connected to the high voltage terminal. The 33 per cent discrepancy mentioned above was further reduced by the fact that the crest value of the voltage of the voltmeter coil was greater than the $\sqrt{2}$ times the effective value. The distortion of the voltage wave of the transformer set and generator is caused by harmonics introduced in the load current by the many corona brushes and multiplied as a result of the reactance through which they flow. As can be seen from Fig. 4 the wave form of the voltmeter coil voltage is practically identical with that of the current through the water resistor, which is connected to the terminal of the transformer set.

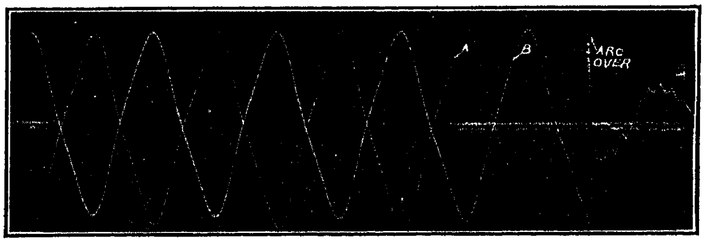

FIG. 3—OSCILLOGRAM SHOWING WAVE FORM OF TRANSFORMER SET AT 1,000,000 VOLTS TO GROUND

A—Current through water resistor connected to high-voltage terminal
B—Voltage wave from voltmeter coil of grounded transformer

Test for High Frequency. After some of the arc-over voltages had been determined by the above methods, it was decided to use sphere gaps as a check, lest there were some high-frequency voltage that could not be recorded by the vibrator element of the oscillograph. The spheres available were two 100-cm. spheres and two 50-cm. spheres. It was decided to make up two gaps, one for each side of the transformer set, in order to keep a symmetrical set-up, since for all previous tests a water column had been used on both sides to preserve the balance of load.

The 50-cm. spheres were mounted so that their centers were about 4 feet from the concrete floor. Above these the 100-cm. spheres were suspended from the roof trusses by a string of 30 insulator units, Fig. 5. This is not a standard sphere-gap set-up. However, it was determined that the voltage values as given by the theoretical curve for breakdown of a gap between 100-cm. spheres for separations up to 100 cm. would be within 10 per cent of the values for breakdown of the gap here used. For this set-up, the smallness of the lower sphere is partially offset by the proximity of the 50-cm. sphere to ground. This value was based on measurements that showed the charging current to the high potential sphere to be twice that to the grounded sphere for a 50-cm. gap between 50-cm. spheres.

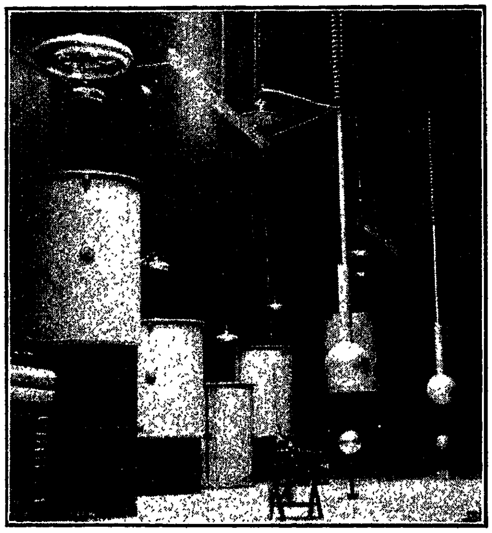

FIG. 4—SPHERE-GAPS AS USED TO CHECK POINT-GAP VOLTAGE

These sphere gaps were used in connection with various point gap settings. For each gap setting the spheres were adjusted so that the arc-overs were about equally divided between the point gaps and the sphere gaps. The voltage was then determined by means of the water resistor and oscillograph. The following table shows the results for three gap settings.

Separation of points	Separation of spheres	Arc-over voltage*		
		Point gap (kv. to gv.)	Sphere gap	Voltages for corresponding separation of 100-cm. spheres
16 ft.	70. cm.	854 kv.	861 kv.	880 kv.
20 ft.	83.5 cm.	942 kv.	945 kv.	946 kv.
22 ft.	102.5 cm.	982 kv.	988 kv.	1020 kv.

*Each voltage value is the average of 3 observations.

The sphere gap was not used in connection with the point gaps in excess of 24 feet due to the fact that the limit of this type of gap had been reached. The results as given in the above table would indicate that the oscillograph was recording correctly the voltage that was impressed on the respective gaps. Since the normal rating of the transformer set is 2100 kv., the point gap calibration was continued up to a distance of 26 feet and later to 30 feet. Fig. 12 shows the arc following breakdown of a 30-foot gap between points. For this gap the transformer set is operating slightly above rated voltage, and as a consequence, the voltage was in every case raised rapidly to arc-over.

When the two sets of sphere gaps were being used with the 22-foot point gap, a very interesting thing was observed. During a preliminary test one of the 50-cm. spheres and its mounting were removed, leaving an 8-foot clearance from the 100-cm. sphere to ground. With the other sphere gap set at 100 cm. the voltage was raised, and it was surprising to find that the one 100-cm. sphere arced the 8-foot to ground. This distance was more than twice that between the other spheres. The voltage was applied a number of times with the same result. The 50-cm. sphere that had been taken out was replaced and the gap adjusted for 110-cm. The voltage was then applied and the 100-cm. gap arced over. This performance was repeated for the sphere gap on the other side of the set with a similar result. Calculations do not conform to this observed condition, and with what other information is available, at the present time, it is difficult to account for this action.

Test of Symmetry of Transformer Set. To be sure that there was no error in the assumption that the two sides of the transformer set were symmetrical with respect to ground, simultaneous oscillograms were taken of the current through the water resistors on each side of the set. Determinations from these oscillograms and the water column resistances gave the voltages to ground on the two sides of the set as 915 kv. and 930 kv. This difference is within the limit of the measurements.

Shielding of the Water Resistor. The water resistor was partially shielded by a 3-ft. horizontal circular disk at the top. (See Fig. 5.) For voltage measurements the shielding need not be nearly as perfect as for wattmeter work.[7] The charging current entering or leaving the resistance, because of imperfect shielding, may affect the phase angle for low power factor wattmeter measurements, but such current must be of relatively large value before it affects greatly the actual magnitude of the current through the high resistance. In order not to depend too much on such assumptions as to the correctness of shielding, simultaneous oscillograms were taken at the top and at the bottom of the water resistor. The oscillograph at the top was a

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7. *Some Features and Improvements on the High-Voltage Wattmeter*, J. S. Carroll, A. I. E. E. TRANS., Vol. XLIV, 1925, p. 1010.

small two-element oscillograph, operated with a small motor. Both the oscillograph and the motor were adapted to be operated from a 6-volt storage battery. These were all enclosed in a wire screen cage which shielded them from corona effects and external electrostatic fields, (see Fig. 6). The turning on and off of the small incandescent light in the oscillograph at the proper instant was used instead of a shutter. This operation and also the motor control were accomplished by means of switches operated by linen threads controlled by relays. The results of this test were as follows:

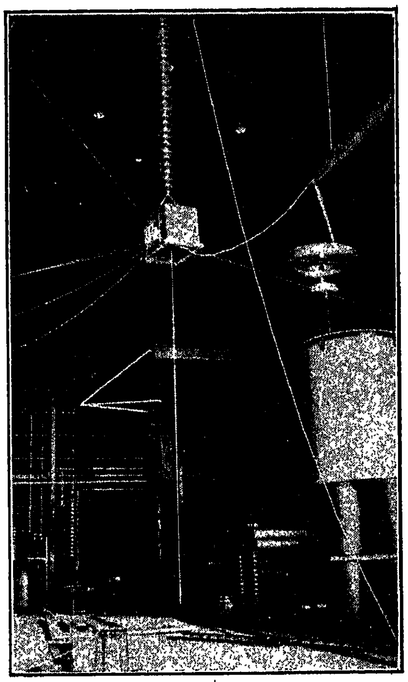

FIG. 6—WATER RESISTOR AND OSCILLOGRAPH IN SHIELDING CAGE AS USED FOR MEASUREMENTS AT HIGH POTENTIAL

Record No.	Current at top of resistor	Current at bottom of resistor	Percentage of difference
1	52.7 milliamperes	51.7 milliamperes	1.9 per cent
2	49.1 milliamperes	48.2 milliamperes	1.8 per cent

The difference in these two currents is within experimental error, so it was decided that no appreciable error was introduced into our results on account of improper shielding. On account of the dimensions involved, the capacitance of this water resistor to the ground or to the high voltage shield and connections is so small that even though there is some distortion in the electrostatic field, the current flow caused by this distortion is extremely small.

Another test that was made on the shielding was in connection with the use of the sphere gap of 100-cm. spheres. With the gap set at 100-cm., the arc-over voltage was measured with a water column resistance of 30 megohms and also with 10 megohms. Since there was nothing changed except the resistance of the water resistor, the capacitance current due to improper shielding remained practically constant. If this charging current were appreciable, the voltage as measured with the 10-megohm resistor would be noticeably different from that measured with the 30-megohm resistor. The average of 10 records in each case gave 994 kv. when the 30-megohm resistor was used and 1004 kv. when the 10-megohm resistor was used. This again shows that the resistor was shielded sufficiently for voltage measurements.

DISCUSSION OF RESULTS

Points Gap. The full-line curve of Fig. 7 shows the arc-over voltage between two points for distances from 8 feet to 30 feet for the neutral grounded condition in which both points are at high potential. The points were ⅝-inch brass rods tapered to a point in a distance of 3 inches. The height of the gap from the floor was approximately 30 feet. The plotted points are averages of from 5 to 20 observations. The data from which these points were plotted showed a maximum difference in readings of less than 10 per cent of the mean value. No correction was made for air density or humidity for any of the point-gap curves for such a correction was seldom greater than 2 per cent when calculated by present accepted methods.[4]

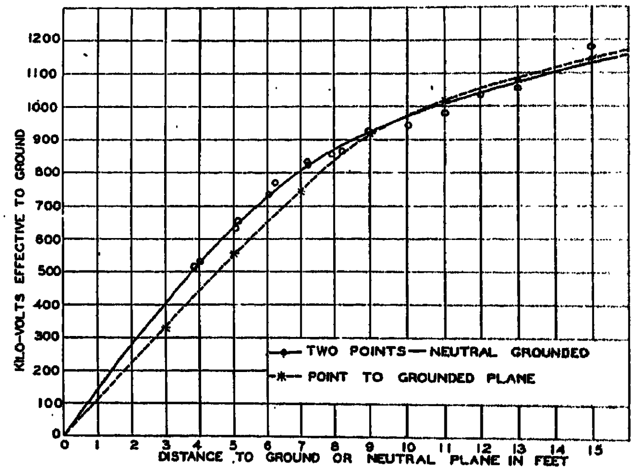

FIG. 7—SPARK-OVER VOLTAGE FOR POINT GAPS

Full line, two points, neutral grounded
Broken line, point to grounded plane

Arc-over voltages were determined for a point to plane set-up for distances from 3 feet to 15 feet. The point was mounted vertically above the floor, a nine-foot square section of which was covered with a sheet iron plate. The results of observations on this set-up are plotted in the dashed line of Fig. 7. The maximum variation in arc-over voltage for this set-up was seldom in excess of 5 per cent of the mean value. Plotted points are the average of four or more observations for the given gap setting.

The present practise in transmission line design is to use a dry insulator flashover that is approximately three times the line to line voltage[8] for all voltages in excess of 165 kv. The change in the slope of the curve of point to plane arc-over (which is practically equivalent to the line to tower arc-over), with increase in voltage in excess of 900 kv., shows that the added tower clearance required will undoubtedly be a limiting factor in high-voltage transmission.

The curves of Fig. 7 show that the arc-over voltage for a point to grounded plane is practically equal to the voltage to neutral between two points at high potential when the distance arced over between the points is twice that of the point to plane.

Fig. 8 shows the effect of ground on the arc-over voltage of a vertical point-gap 9 feet in length as the distance from the lower point to ground is changed. Each observation is plotted separately. The apparent dropping of the curve as the gap is raised from the ground plane in excess of 15 feet is due to the lower or ground point nearing the high voltage connections and thus increasing the voltage gradient on the lower point, and also due to the fact that the upper point has reached a position with respect to the ground and sides of the building where a further increase in the distance to the floor has little effect upon the field intensity in the vicinity of the point.

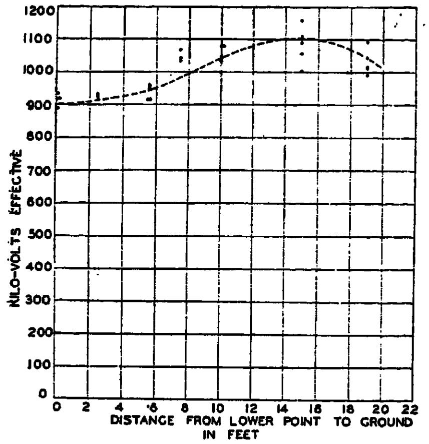

FIG. 8—EFFECT OF GROUND PROXIMITY ON ARC-OVER OF 9 FT. VERTICAL POINT-GAP

Lower point grounded

100-Cm. Spheres. Due to some inherent surface property, which is as yet undetermined, the action of the 100-cm. aluminum spheres is rendered rather erratic where the separation between the spheres is in excess of 75 per cent of their diameter, and for smaller separations this erratic action may come in to a less degree. Observations were taken on both the 100-cm. spheres and 50-cm. spheres and in practically every case, many of the arc-overs were observed to be much lower than the theoretical voltage for the gap setting. It must be remembered, however, that this action is greatly increased when the separation between the spheres approaches the sphere diameter. A typical set of readings is given in the following table for values of the Hendrix voltmeter coil voltage for 50 successive arc-overs of the 100-cm. spheres spaced 100 cm. These were the first values following cleaning and polishing of the spheres and are characteristic of many similar sets obtained during these tests.

Arc-over No.	Voltmeter reading	Arc-over No.	Voltmeter reading
1	19	31	30
2	19	32	29
3	24	33	31
4	24	34	30.6
5	24	35	30.6
6	24.5	36	30.6
7	24.5	37	29.5
8	24.5	38	27
9	26	39	28
10	24	40	No vm. reading
11	26	41	
12	25	43	
13	26	44	
14	26	45	29.5
15	24	46	30.7
16	27	47	30.8
17	27	48	31
18	Voltmeter was not read	49	31
19		50	31
20			
21			
22			
23			
24			
25			
26	30		
27	28		
28	27		
29	30.6		
30	29.6		

From the above values it can be seen readily that at least 50 applications of voltage were necessary to get the spheres in condition. This fact by itself is no small item when it comes to wear and tear on high-voltage transformer test sets. Such a conditioning was found to be necessary to a greater or less degree if the spheres remained unused for more than 6 to 8 hours. This condition makes the voltage as determined by the sphere gap somewhat uncertain unless particular precaution is taken to condition the spheres. It can be said that the arc-over voltage for a given sphere gap setting will not exceed a definite value, which is very close to the theoretical value as given by Mr. F. W. Peek, but the arc-over voltage may be as low as 50 per cent of this value.

The use of the sphere gap for determining insulator flashover voltage has many disadvantages. A sphere gap cannot be used to measure the exact voltage at which an insulator string will arc over but can only be set so that it will arc over about equally with the insulator string. This means that the higher voltages that would have been impressed across the insulator string will arc the spheres due to the fact that the spheres will limit the voltage that may be applied. The character of these higher voltage arc-overs of insulators should be known even though the voltage applied at the time of arc-over may be only 5 per cent in excess of that which is observed with the spheres in the circuit as a measuring gap.

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[8] F. W. Peek, *General Electric Review*, Feb. 1922, Vol. 25, p. 114.

In Fig. 9 the full line shows the calibration curve of the meter sphere gap that was determined by the water-resistor-oscillograph method of voltage measurement. The values plotted are averages of the records taken. The broken lines show the values as calculated by Mr. F. W. Peek. The difference between these curves is practically negligible for sphere separations up to 70 cm. For separations greater than 70 cm. the difference increases, but at 125 cm. it is only 5 per cent. The maximum values obtained agree in all cases with the theoretical values of Mr. Peek as mentioned in an above section. The slight difference in the curves in the range between 10 cm. and 60 cm. separation is due to a slight correction necessary for the increased clearance to ground as used by the authors.

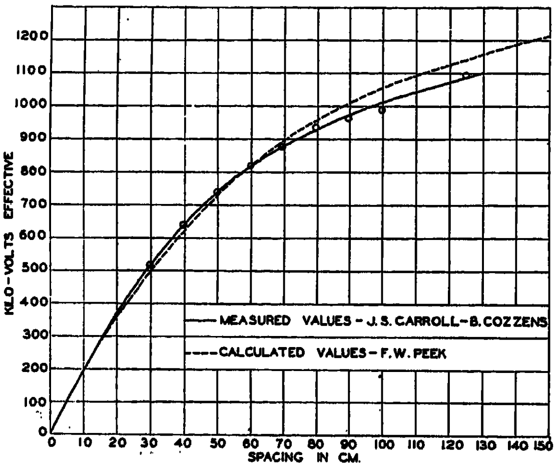

Fig. 9—Theoretical and Measured Values of Sphere-Gap Sparkover Voltage for 100-Cm. Spheres

The plotted points are averages of the measured values

After the calibration of the meter sphere gap was completed this gap was paralleled with the gap of 50-cm. spheres. The meter spheres were set at 30 cm. and the the 50-cm. spheres adjusted so that the arc-overs were equally divided between the two gaps. This gap setting on the 50-cm. spheres was 55 cm. According to this measurement the arc-over voltage for the 50-cm. spheres at this spacing is 8 per cent below that calculated by Mr. Peek. Time would not permit of a complete calibration of the 50-cm. sphere gap.

In all cases where records were taken the arc-over current of the gap was less than two amperes and the duration of the arc was limited to six cycles. This value of current and duration of arc caused no noticeable pitting of the meter aluminum spheres. These spheres were arced over more than 1000 times during the tests reported in this paper.

Corona Current from a Point

During the process of taking these records the question arose as to the amount of current that was drawn through the 500,000-ohm protective resistance that was connected in the high voltage circuit at the terminal of the line transformer. This current was the combination of the current through the water resistor, charging current to the connections, and the corona current from the point and connections. For the measurement of this current a shielded two-element oscillograph was used, the one element being connected in the water resistor circuit and the other used to record the total current from the load end of the protective resistance. The crest value of this total current was found to be 154 milliamperes when the voltage of the point to ground was 1,000,000 volts.

While this set-up was in place it was decided to obtain a record of the corona current from one of the points of the points gap a few cycles before the arc-over of a 24-ft. gap. The lead from the oscillograph element was completely shielded up to the point. (See detail of Fig. 10.) This arrangement eliminated all charging current and permitted the measurement of only the corona streamers from the point. The shielded cage set-up was similar to that shown in Fig. 6. The operation was as follows: The generator oil switch and main field switches were closed and then the oscillograph motor was started by pulling a string that changed the position of the switch S_1 from a to b. The auxiliary field switch was then closed shorting out the field resistance and the voltage began to build up. Approximately one-half second later the motor operated cam closed a contact that operated a trip that pulled a string and changed the position of switch S_2 from c to d. This lighted the incandescent lamp in the oscillograph and at the same time energized the magnets $W W$. This released the switch S_3 from position e and was delayed in reaching position f by means of a kodak timer. This time delay was approximately 0.25 sec. When the contact at f is made the oscillograph shutter is released to the open position by the magnet $X X$. The current through the water resistor and the corona current from the point were then recorded for approximately 14 cycles before the arc-over of the gap. When the gap arced over, the overload relay opened the generator oil switch and when this switch had reached

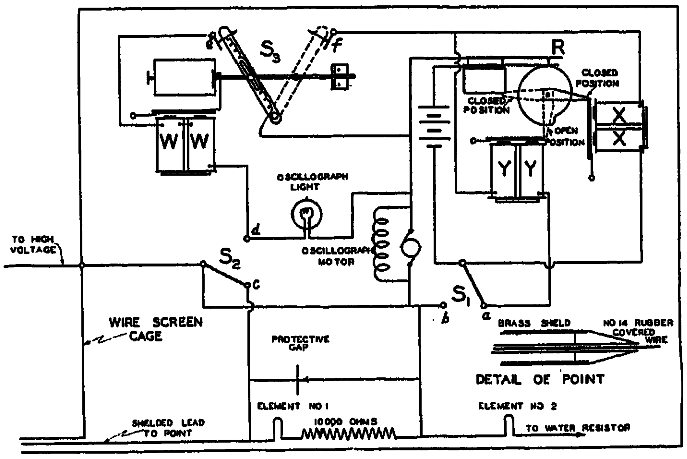

Fig. 10—Measuring and Control Circuit used in Obtaining Record of Corona Current from a Point at 1,000,000 Volts

the end of its travel a contact was closed that operated a relay which pulled a string changing the position of switch S_2 from position *c* to *d*. This energized the magnets *Y Y* and closed the oscillograph shutter. When the shutter is in the closed position the cam on the shutter arm opens the contacts at *R* which opens the battery circuit, thus stopping the motor and turning off the light. The time required for this operation delays the closing of the shutter after arc-over sufficiently to record a zero line on the film.

The necessity for turning on the oscillograph light a quarter of a second before the shutter was opened was due to the fact that as the filament heats up there is a slight change in its position which causes a considerable shift of the spot on the film, in some cases amounting to almost as much as a quarter of an inch. Heating the light up to full brilliancy before the shutter is opened and keeping the shutter open after arc-over until the zero line is taken eliminates any possible shift of the record or the zero line due to this cause. This magnetically controlled shutter which was used on the small two-element oscillograph was designed and built by the authors.

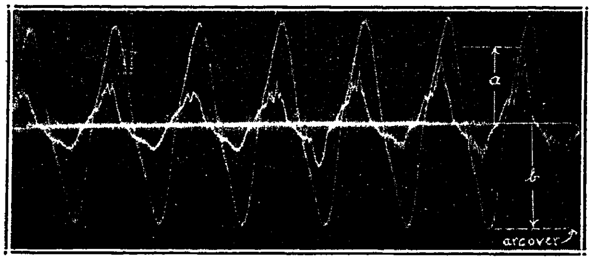

FIG. 11—CORONA CURRENT FROM A POINT

The irregular wave is the oscillogram of the corona current, from a point 1,040,000 volts effective to ground

The crest value of the current at (*a*) is 28 milliamperes

The smooth wave is the current through the water resistor

The crest value of the voltage at (*b*) is 1,470,000 volts

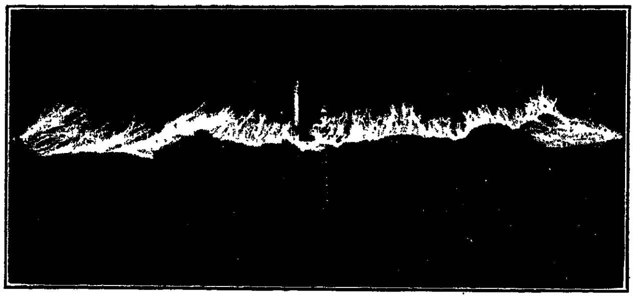

FIG. 12—ARC FOLLOWING BREAKDOWN OF A 30-FT. GAP BETWEEN POINTS, 2,380,000 VOLTS EFFECTIVE

In order to protect the sensitive oscillograph element (No. 1), which is connected to the point, from being burned out with the arc-over current of 1.5 amperes, the 10,000 ohm resistance was connected in series with the element and a gap shunted across the two. This gap consisted of a blunt point separated from a plate by the thickness of a cigarette paper. This proved ample protection for the oscillograph element because a great number of arc-overs was recorded with absolutely no injury to the element.

Fig. 11 is one of the records taken in this manner. The smooth wave is the current through the water resistor and the irregular wave is the corona current from the point. It is interesting to note that no two cycles of the latter have the same form. The apparent difference in phase angle of this current and voltage wave is due no doubt to a space charge effect. The current reverses before the voltage reaches zero because of a reverse field that is set up by the charge that remains in the space about the point until it is reversed during the following half cycle.

CONCLUSIONS

1. The Water Resistor-Oscillograph method for voltage measurement is adaptable for use with 60-cycle transformer test sets for the measurement of arc-over voltages.
2. Points gaps can be used for 60-cycle voltage measurements with an error of less than 10 per cent.
3. The sphere gap of one-meter aluminum spheres requires considerable preparation preliminary to using it as a basis for 60-cycle voltage measurement. For voltages in excess of 900 kv. this preparation is such as to render their use undesirable.
4. The maximum 60-cycle voltage that may be impressed on a gap between one-meter spheres is given by the theoretical value for sphere gap breakdown as determined by Mr. F. W. Peek.
5. The breakdown of a gap between meter spheres may be as low as 50 per cent of the theoretical breakdown voltage depending upon the previous treatment of the spheres.
6. The rapid decrease in kv. per inch necessary for the breakdown of gaps in excess of 9 ft. to ground establishes an approximate economic limit of high voltage for power transmission based on present design practise.

ACKNOWLEDGMENTS

This report would not be complete without calling to the attention of those not already acquainted with Dr. Ryan, the extent to which his past experience aids in such an undertaking.

The authors wish to mention Dr. J. T. Lusignan, whose assistance was of much value.

EQUIPMENT USED

2,100,000-volt set consisting of six 350-kv., 350-kv-a.
transformers built by the General Electric Company,
Power was supplied to the transformers through a
General Electric Co. motor generator set,
4000-volt, 550-hp. Synchronous Motor
2300-volt, 1800-kv-a. Sine Wave Generator.

The nine-element oscillograph and the two-element "osiso" were made by the Westinghouse Electric and Manufacturing Company.

The power circuit analyzer used in some of the wave analysis was built by the American Telephone and Telegraph Company.

The two one-meter aluminum spheres were made for Stanford University by the Southern California Edison Company.

The sphere gap of the two 50-cm. spheres was made by the General Electric Company.

Discussion

E. C. Starr: The method used by Messrs. Carroll and Cozzens for voltage measurement is fundamental and direct, not being dependent upon transformer ratios, etc., but is subject to considerable error unless proper precautions are taken. Water-tube resistances can change very rapidly, particularly under changing conditions of current flow, and the charging current of a long water tube, part of which is operating at potentials of 1,000,000 volts and more, is of considerable magnitude. It seems, however, that the methods employed should give the proper resistance values and that the shielding devices should reduce the charging currents in the water-tube multiplier to a negligible quantity. These charging currents are, of course, in quadrature with the resistance currents and are not directly additive.

One possible source of error apparently was not investigated. Work with the cathode ray oscillograph has shown that the long, snapping streamers accompanying the corona discharge from electrodes at large spacings set up relatively large transient currents of extremely short duration in the supply circuit. These currents induce (in supply circuit) transient voltages which may have a considerable influence upon the apparent arcing voltage, particularly of sphere gaps. The ordinary Duddell oscillograph is not fast enough to record transients of this character.

It was found in this investigation that the rupturing gradients of extremely long point-gaps were much lower than for gaps of 10 ft. or less. It has been accepted rather generally that this gradient for all gaps greater than 4 or 5 ft. in length is about 100,000 volts (effective 60 cycles) per foot. I should like to suggest as a probable explanation of the observed discrepancy that the relative nearness of grounded objects and high-voltage conductors, transformers, etc., to the electrodes of the gaps at the extreme spacings created much greater flux concentration at the electrodes than would exist if the gaps were isolated in space. Hence, arc-over took place at lower apparent gradients at these extreme spacings than at shorter spacings when the ratio of gap clearance to gap length was much greater. Clearances of about 30 ft. were obtained for these tests but it is observed that the longest gaps investigated were nearly 30 ft. in length.

It is very difficult to obtain clearances of two or three times the gap length when we are dealing with gaps of 20 or 30 ft. but it is necessary that such clearances be obtained if the apparent rupturing gradients for the long spacings are to be of the same order of magnitude as for the short spacings. The Ryan Laboratory at Stanford University has clearances as great as those of any present indoor laboratory and the authors made an effort to use all available clearance, but the results seem to indicate that the proximity effect was entering to a pronounced degree.

The difficulties experienced with the 100-cm. sphere gap are interesting. A slight deviation of the actual from the calculated spark-over curve at the higher values might be expected, inasmuch as the calculated curve is based upon rupturing gradients as determined by much smaller spheres. As a measuring device, however, the gap should not be erratic, providing all conditions of operation are normal. Such conditions obtain when, for any normal spacing and voltage, the electrostatic field between the spheres is much more intense than between either sphere and surrounding objects. I have seen a 100-cm. sphere gap function very erratically at wide spacings when located in a region of strong extraneous fields. Arcs would occasionally start between the nearest surface of one sphere and a point nearly 90 deg. from the nearest surface of the other sphere. However, when these spheres were removed to a region of large clearances and small extraneous fields, their operation was perfectly normal.

When a sphere gap is set at spacings approaching the sphere diameter and the clearance to ground or other conductors is not materially greater than the point-gap arcing distance, the dielectric field between the spheres may be so distorted as to cause the arc-overs to be very erratic in voltage and character. The difficulties experienced by the authors with their 100-cm. sphere-gap operating at potentials of the order of 1,000,000 volts may have been of this nature. There should be nothing inherently wrong with the 100-cm. sphere-gap. The difficulty lies in obtaining sufficient isolation to eliminate the appearance, at the extreme voltages, of disturbing fields.

Reference was made to a condition in which a 100-cm. sphere was suspended above a 50-cm. sphere located a short distance above the floor. It was observed that arcs actually took place between the upper sphere and the floor at lower voltages than were required to arc the gap with the lower sphere in place. The weakest type of gap is that of a point to the concave side of a hemispherical surface. The next weakest is that of a point to a plane. With the lower sphere removed the condition obtaining is that of a sphere to a plane and, as Mr. Cozzens brought out, at the larger spacings a sphere approaches a point in effect. This gap would be relatively weak if the field were distorted by near-by projections on the floor. However, when the lower sphere is in place a certain symmetry of field is forced and the gap might actually become stronger.

In dealing with extremely high voltages the proximity effect becomes very important. Corona streamers of considerable length shoot out from conductors and electrodes and field distortion may produce gradients of nearly a rupturing value simultaneously in several directions.

The authors state that it was necessary to "warm up" the 100-cm. sphere-gap by taking about 50 arc-overs before the performance could be relied upon. I should like to know if, after these preliminary readings were taken, the gap was still somewhat erratic, or if it became fairly constant in its performance.

H. V. Carpenter: I should like to ask the authors in regard to the points where they measured the corona. Were the two points symmetrical, or was the corona measured from one point to something else?

I think we have all felt there were questions regarding the sphere-gap. Here we find a move in the direction of getting a substitute instrument which, while it is somewhat cumbersome and requires developing of photographic film, perhaps is still in a sense a direct-reading, single-observation instrument, which is something very desirable in measuring high voltages.

I believe the authors should give more data regarding the clearances to show as definitely as possible just where the limitations come, due to the distances from surrounding objects and the character of those surrounding objects.

L. J. Corbett: A year or two ago Dr. Reukema of the University of California presented the results of some researches which he had made in regard to the operation of sphere-gaps under the action of ultraviolet light. I think the effect was that the ultraviolet light caused the initial ionization of the air and made the spark-over value more definite. He did not get such non-uniform results as appear to have been obtained by Mr. Carroll. I merely call attention to this as a possibility for improvement in our methods of research in such fields.

R. W. Sorensen: For a long time we were quite satisfied, when a suitable electrostatic voltmeter was not available, to measure voltages with a spark-gap, utilizing sharp sewing needles as points. I still think for the practical purpose of insulation testing this means of measuring voltage was within certain limits very satisfactory. In the course of the increase in voltage the sharp needle gap was found at the higher voltages to be difficult to use in the duplication of results, and we had the development of the sphere gap.

For certain ranges of voltage, say up to 500,000 or 700,000 volts, the sphere-gap has shown itself to be a very satisfactory device, and should not be condemned without very careful consideration for use at voltages even higher. With higher voltages, however, we must be exceedingly careful about the location of the spheres and the objects surrounding them.

These authors have suggested that for the high voltages there are some advantages in the needle-gap over the sphere-gap. In some work I have done we have found it very convenient to use a needle-gap having blunt needles. With such needles we can duplicate test results fairly well, and we feel that we have a fair degree of accuracy by the use of such needles, an accuracy of say 5 or 10 per cent. It is true that as the voltage is brought up there is a large amount of corona around the needles before arc-over. This corona action, however, has a tendency to equalize the field and give proper distribution before arc-over, and does not, therefore, indicate a much lower arc-over potential than would be the case with spheres if the spheres are not very large. It would seem to me, therefore, that we should not too hastily condemn the sphere-gap and the work which was involved in establishing the sphere-gap as a standard for measuring of voltage; but rather, we must say that changing conditions have made it necessary to develop an additional system of voltage measurement which permits reasonable accuracy with less effort than can be accomplished by means of the sphere-gap.

In dealing with voltages which produce these long arcing distances it seems inevitable that there will be erratic arc-overs. The X-ray tube which Doctors Lauritsen and Bennett have recently been operating with one million volts in our laboratory, has shown in its operation that we can have very erratic flash-overs, but also they have shown that by properly distributing the field by means of shields each in the shape of a torus the air between terminals can be stressed very highly without arc-over. The X-ray tube to which I refer has a length of four times the glass cylinders commonly used on gasoline measuring tanks. Between the ends of the glass column built up of these four cylinders these men have applied more than a million volts without arc-over. In the early experiments, the torus rings which are placed between the sections of the glass column as built up were connected to definite voltage points with the expectation of improving arc-over voltage. We found, however, that connecting the rings thus was not as satisfactory as leaving the intermediate rings to float free, each to assume a natural potential in the field. The reason for the erratic arc-overs is very difficult to determine, though it is probable that some of them are due to gas pockets near the surface of the spheres from which the gas is easily pulled out. Such an explanation could account for Professor Carroll's having to arc-over his sphere-gaps about fifty times before they are stable in the sense of giving results which are easily duplicated, because after the gases have been driven out the arcing voltage would no longer be influenced by elimination of these gases from the sphere electrodes. This latter phenomenon is very common in the study of arc-over distances between electrodes in a high vacuum, and it may be that something similar takes place in air.

J. S. Carroll: One of the points that Mr. Cozzens emphasized at the beginning of the presentation of this paper was that the calibrations given in the paper are not put forth with the intention of having them accepted as standards. A standard calibration for a point-gap would be an extremely difficult task. Because of the large separation of the points at these voltages, clearances affect the arc-over voltages to a considerable degree. This is shown in Fig. 8 of the paper. Also I believe that the relatively large clearance in case of the 8-ft. to 12-ft. point-gap is somewhat responsible for the high average voltage gradient and the relatively small clearance for the 30-ft. gap would tend to decrease the average voltage gradient. However, it must be pointed out that these clearances would not seriously affect the point-to-plane arc-over voltages.

I am glad that Mr. Starr related to us some of his experiences in working with high voltages. We find that these erratic sphere discharges are not a peculiarity of the high-voltage laboratory at Stanford. Many who have witnessed the performance of the meter sphere-gap do not seem to have any considerable amount of confidence in it for voltages above 700 kv.

The question has been asked by several persons as to just how long the meter spheres remain conditioned after cleating them up with about 50 arc-overs. If the spheres had been left unused for half an hour we would arc them over a few times before taking an observation. Even with that precaution we would get a very low value of voltage every once in a while that had to be discarded. If the spheres stood idle over night it usually required about the 50 arc-overs to recondition them.

It might appear presumptuous on our part to assume that our error of observation was less than 1 per cent but it is interesting to note that the maximum observed values of arc-over voltage for each gap setting lie on Mr. Peek's curve, none of them is above it. Our values are averages of from four to eight observations. We, ourselves, are satisfied that the sphere-gap was not arcing over at its maximum voltage every time. We thought the information in the observed data was of sufficient importance to be published and we find we were justified in this conclusion by the numerous questions that have been asked concerning the nature of it.

In regard to Mr. Corbett's question concerning the effect of increasing the initial ionization about the spheres previous to arc-over by some such means as using ultraviolet light. That was tried with the 50-cm. spheres but with a 400-watt quartz-mercury arc placed within about 5 ft. of the spheres we were unable to detect any difference due to its presence.

In answer to Dean Carpenter's question as to the nature of the set-up for the taking of the corona current oscillograms, I wish to state that this corona current was from one of the points of a 26-ft. point-gap in which the two points were at high potential. Sometimes we want to compare this current with a current from a point to a grounded plane.

Several people have made suggestions as to some of the things that might affect the arc-over voltage of the sphere-gap. The matter of clearance is an item but I do not think it is a very large factor if clearances of at least four diameters are maintained. Furthermore this should produce a constant error and would not in any way account for the erratic performance of the gap. When the spheres would arc-over at the side instead of directly between them there was no tendency for the arc to confine itself to any particular side. The variation of the ionization of the air about the gap I believe is a relatively small factor, because the normal ionization of the atmosphere is completely disturbed by the presence of the corona brushes from the high-voltage connections, and, as I see it, the arcing over of the spheres would not clear up the air about the spheres. From the experience we have had with the sphere-gap we are practically convinced that the erratic behavior of the spheres is due to the surface condition, the exact nature of which it is difficult to conceive.

As stated in the paper the erratic performance of the sphere gap increases with the size of the sphere and with the increase in spacing. It is a difficult matter to compare the performance of gaps between say 50-cm. spheres with gaps between 100-cm. spheres.

We have used the sphere gaps only in a vertical position so that we cannot say anything as to their behavior if used in the horizontal position. The only time I would expect the spheres to be used in this latter position would be when both spheres are at high voltage. Time did not permit us to mount the spheres and make this test.

Professor McMillan asked what effect the material of the spheres would have on the performance of the gap. We cannot say definitely. The largest copper spheres we have are only 25 cm. in diameter, and with those we know that, to begin with, at least the first three arc-overs are quite likely to be low.

The question in regard to the use of water columns for practical metering is not quite clear. Water columns are very convenient and fairly accurate for laboratory measurements but are not suitable for connecting to a power line for commercial metering.

High-Voltage Gaseous-Conductor Lamps
Electrical Characteristics of the High-Voltage Neon Type

BY F. O. McMILLAN[1]
Member, A. I. E. E.

AND

E. C. STARR[2]
Non-member

***Synopsis.**—Gaseous-conductor lamps are finding a wide field of application in advertising and display lighting.*

A brief discussion of the theory of the high-voltage type is included.

The electrical characteristics of typical high-voltage lamps were investigated by the use of indicating instruments, Duddell and cathode ray oscillographs.

Characteristic curves, data, and oscillograms are given.

Power-factor improvement was studied and data covering two methods of correction are included.

INTRODUCTION

THE field of application of the gaseous-conductor lamp is expanding very rapidly. In the form of neon signs, which are growing in popularity, it will probably soon include a large percentage of the total electrical sign load of the more progressive communities.

The investigation covered in this paper was undertaken in order to determine the various electrical characteristics of typical commercial neon sign lamps of the cold-electrode high-voltage a-c. type. Means of correcting the normally low, lagging power factor were also investigated.

There are several other types of gaseous-conductor lamps including the low-voltage hot-cathode type, the negative-glow type, the electrodeless induction type, and the television type. These are not considered in this paper.

THEORY OF GASEOUS-CONDUCTOR LAMPS

The usual form of high-voltage gaseous-conductor lamp consists of a length of glass tubing containing gas at low pressure and equipped with sealed-in electrodes. The gas pressure is adjusted to a value that gives the lowest possible ionizing potential consistent with good tube life. Visible radiation accompanies the ionization by collision phenomena created when a sufficiently high potential difference is maintained between the two electrodes.

Various colors of light are obtained by the use of different gases and gas mixtures in conjunction with different colors of tubing. Twelve or more shades and colors have been obtained by this means.

A characteristic of all gaseous conductors is that the voltage drop between electrodes after the discharge has been initiated is practically independent of the current flow. Consequently it is necessary, when supplying energy to lamps using gaseous conductors, to provide a circuit having current limiting characteristics because as soon as the discharge starts, the lamp gas becomes, in effect a conductor, the resistance of which is an inverse function of the current.

POWER SUPPLY FOR GASEOUS-CONDUCTOR LAMPS

Because of its ease of voltage transformation and because any space charge effect within the tube is obliterated each succeeding half cycle, alternating current provides the most convenient power source for gaseous-discharge lamps particularly of the high-voltage type. Since the resistance characteristic of the tube is an inverse function of the current flow, the high-voltage transformer used to supply the tube is practically short circuited as soon as the discharge starts. It is necessary then to employ a transformer of high impedance to limit the current flow This impedance must be principally reactance since if resistance were used an excessive amount of power loss would be incurred.

When lighted to approximately the brilliancy employed in the usual neon sign, a 15-mm. neon tube about 11-ft. long requires an input of approximately 50 watts. This power is consumed very largely at the electrodes (due to space charge effect and electron extraction from the electrodes). A tube of half the above length lighted to the same unit brilliancy would require much more than one-half of 50 watts.

EXPERIMENTAL INVESTIGATION

Electrical Characteristics. Several specimens of neon and neon-mercury tubing such as used in commercial neon signs and several neon transformers of the type commonly used for sign lighting were obtained for test. The tubes were each 142 in. in length and 15 mm. (0.59 in.) in diameter. The transformers were rated at 430 volt-amperes 110/12,000-14,000 volts.

Practically all of the data contained in this paper were taken with the same transformer. Slight differences in the construction of different transformers even of the same type and manufacture cause data taken under the same conditions of load and voltage but with different transformers to vary as much as 15 per cent. The data given represent average, typical conditions.

For simplicity in designation throughout the tabulated data and on the curves and hereafter in this paper

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the neon gas filled lamps have been designated as "Neon" and the lamps filled with a mixture of neon, argon, and mercury have been designated as "Mercury."

The curves of Figs. 1, 2, and 3 give the characteristics of series combinations of two neon tubes, two mercury tubes, and one neon and one mercury tube. Two sections of tubing involve the use of four electrodes in series and constitute an average practical condition. It will be noted that the mercury tubes are highest in point of power consumption and power factor while the neon tubes are lowest in these respects. The neon tubes, however, draw the highest current and the mercury tubes the lowest.

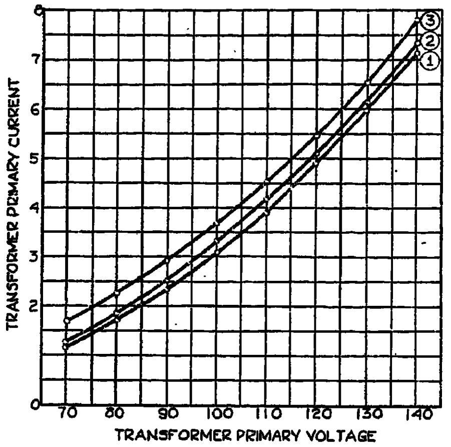


FIG. 1—VOLTAGE-CURRENT CHARACTERISTICS FOR TWO TUBES IN SERIES

1. Two mercury tubes in series
2. One mercury and one neon tube in series
3. Two neon tubes in series

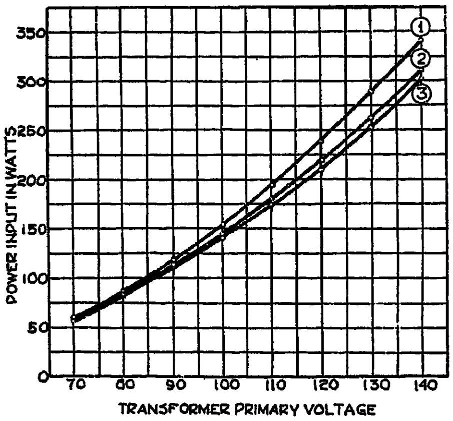


FIG. 2—VOLTAGE-POWER CHARACTERISTICS FOR TWO TUBES IN SERIES

1. Two mercury tubes in series
2. One mercury and one neon tube in series
3. Two neon tubes in series

The power factor at normal voltage (110 volts primary) ranges from 35 per cent for the neon tube combination to 45 per cent for the mercury tube combination and is lagging. As explained before, the resistance characteristic of gaseous conductors is such that a transformer supplying a shunt load of such conductors must possess a high internal reactance in order to limit the load current. A transformer of this character when virtually short circuited draws a current having a large lagging component which increases in magnitude as the resistance of the secondary load decreases. The effective resistance of the mercury tubes is made higher than that of the neon tubes in order to generate sufficient heat to vaporize the metallic mercury. Hence, it follows that a transformer loaded with these mercury tubes should consume more power at a higher power factor and lower current than when loaded with a similar number of neon tubes. The data and curves bear out this conclusion.

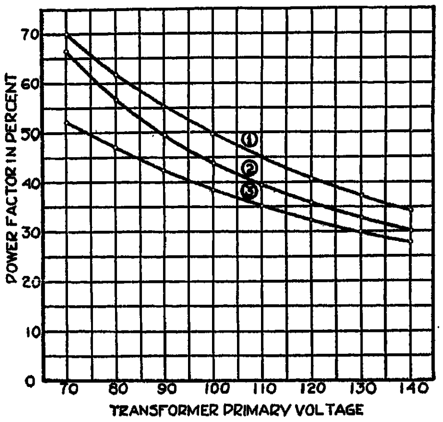


FIG. 3—VOLTAGE-POWER FACTOR CHARACTERISTICS FOR TWO TUBES IN SERIES

1. Two mercury tubes in series
2. One mercury and one neon tube in series
3. Two neon tubes in series

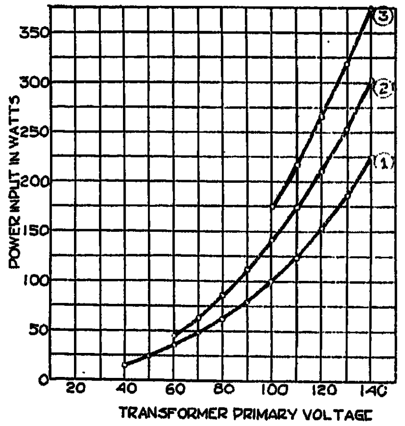


FIG. 4—VOLTAGE-POWER CHARACTERISTICS FOR ONE, TWO, AND THREE NEON TUBES IN SERIES

1. One neon tube
2. Two neon tubes in series
3. Three neon tubes in series

The characteristics of series combinations of one, two, and three neon tubes are given in Figs. 4 and 5. Since the effective resistance of the transformer load depends upon the number of electrodes and length of tubing in series, it would be expected from the previous discussion that the power factor and power consumption would increase and the current decrease as the number of tubes in series is increased. The data and curves bear this out.

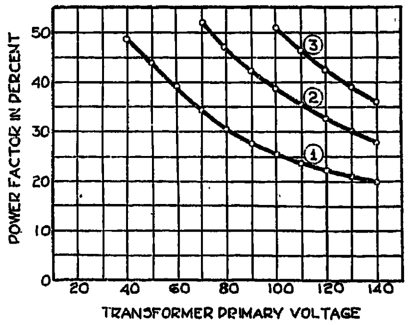
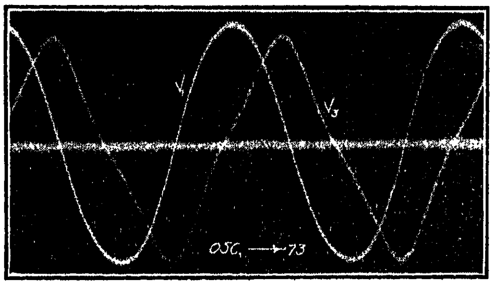


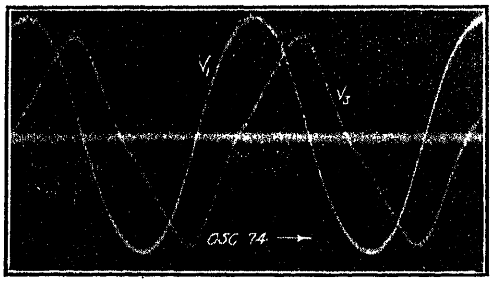
Fig. 5—Voltage-Power Factor Characteristics for One, Two, and Three Neon Tubes in Series

1. One neon tube
2. Two neon tubes in series
3. Three neon tubes in series

In the commercial neon transformers the necessary high impedance is obtained by providing a magnetic shunt on the core between the primary and secondary windings. This shunt increases the leakage reactance of the transformer very greatly. With the transformer operating at 110 volts primary supplying a load of three neon tubes in series the primary current increased from 4.28 amperes with magnetic shunt to 12.8 amperes without magnetic shunt. The power consumption increased from 217 watts to 794 watts. The power factor increased from 0.461 to 0.563. This increased power input to the neon lamps resulting from the removal of the magnetic shunt from the transformer gave a very great increase in brilliancy of illumination. However, this condition is impractical because the volt-ampere load on the transformer is 3.3 times the normal rating.



Load—One neon tube

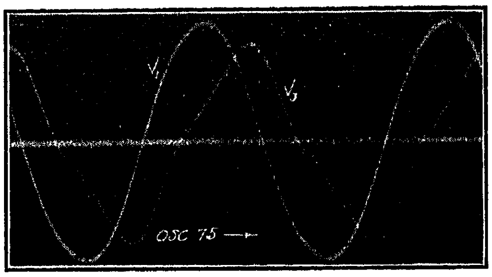


Load—Two neon tubes in series

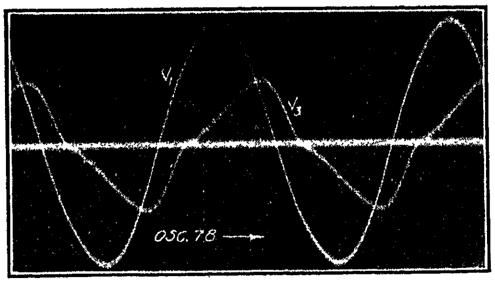
Fig. 6—Low-Voltage Input to Loaded Neon Transformer

V_1 = Voltage 110 r. m. s.
V_3 = Current

Oscillograms of voltage and current were taken on the low-voltage and also on the high-voltage side of a loaded neon transformer. It was necessary to use a potential transformer to obtain the high-voltage wave forms. This potential transformer was a duplicate of the step-up transformer and had an appreciable effect upon the performance. However, cyclograms (Fig. 11) taken by means of the low-voltage cathode ray oscillograph which required no appreciable power (approximately 0.5 watts) showed the general characteristics to be unaffected.



Load—Three neon tubes in series



Load—Three mercury tubes in series

Fig. 7—Low-Voltage Input to Loaded Neon Transformer

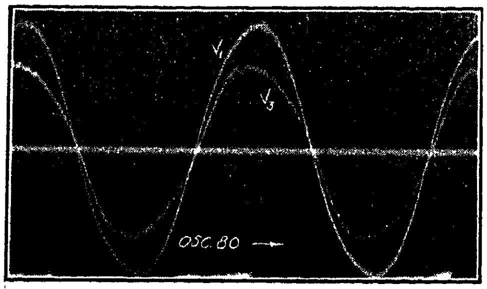
V_1 = Voltage 110 volts r. m. s.
V_3 = Current

The current and voltage input to a transformer supplying first, one neon tube and then two neon tubes in series at normal voltage is shown in Fig. 6. The currents are typical low-saturation magnetizing current waves and for the two-tube case the current is smaller and more nearly in phase with the voltage than for the one-tube case.

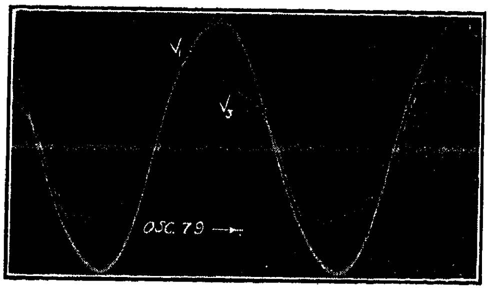
Fig. 7 shows the input voltage and current waves first for a load of three neon tubes in series and then for three mercury tubes in series. The current is smaller and more nearly in phase in the second case.

Fig. 8 was taken under the same conditions of load and voltage as Fig. 7 but in this case the phase angle was reduced to zero by placing static capacitance in parallel with the low-voltage side of the transformer. It will be noted that more corrective volt-amperes were required for the neon than for the mercury combination.

The output voltage and current waves of a loaded transformer are shown in Fig. 9. In the upper oscillogram (OSC. 83), that taken with neon tubes, the very pronounced oscillation in the current wave is due to two factors. The initial part showing little decrement is produced by the impedance drop in the transformer drawing the terminal voltage down so low following each breakdown that the discharge stops only to be reestablished again as soon as the voltage recovers to the ionization potential. The latter part is the free oscillation of the circuit, that is between the capacitance, inductance, and resistance of the transformer and its load. This free oscillation takes place each half cycle after the high voltage has increased to a value high enough to sustain continuous ionization.



Load—Three neon tubes in series
Corrective volt-amperes 418
Corrective capacitance 91.6 microfarads



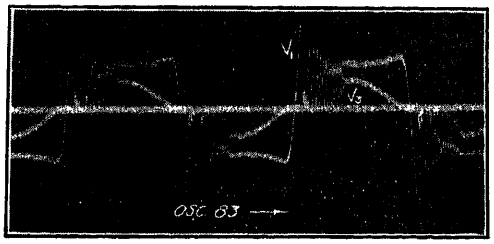
Load—three mercury tubes in series
Corrective volt-amperes 182
Corrective capacitance 39.8 microfarads

Fig. 8—Low-Voltage Input to Neon Transformer with Power-Factor Correction

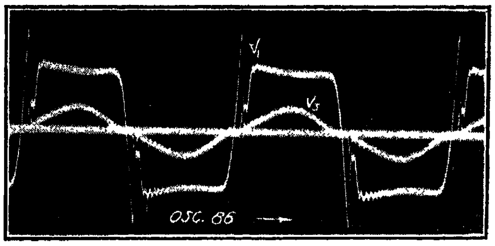
V_1 = Voltage 110 volts r. m. s.
V_3 = Current

In the lower oscillogram of Fig. 9 (OSC. 86), that taken with mercury tubes, the current is lower, oscillations are much less pronounced, and sustained voltage is higher than in the neon-tube case. All of these effects are produced by the increased resistance of the mercury tubes.

The voltage waves are interesting. In both oscillograms, at the start of each half cycle, the voltage rises from zero at a rapid rate following the normal open-circuit secondary sine wave until the ionizing potential is reached. At this voltage sudden breakdown occurs, current begins to flow, and the circuit is set in oscillation.



Load—Two neon tubes in series



Load—Two mercury tubes in series

Fig. 9—High-Voltage Input to Neon Tubes

V_1 = Voltage of two tubes
V_3 = Tube current

This oscillation continues without decrement, as previously explained, until the voltage wave increases to a sufficient value to maintain continuous ionization. At this point the free oscillation of the circuit begins and is damped out by the resistance of the tubes and transformer. Then as the voltage attempts to rise still further, the ionization increases, a greater current flows, a greater transformer impedance drop results, and the terminal voltage remains practically constant until the normal voltage wave decreases to this constant value. At this instant ionization ceases, the voltage

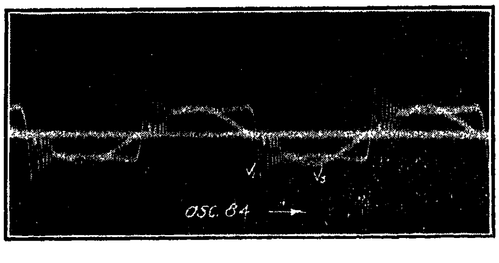


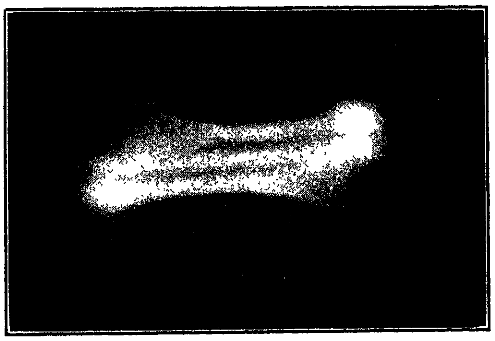
Fig. 10—High-Voltage Input to One Neon Tube

V_1 = Tube voltage
V_3 = Tube current

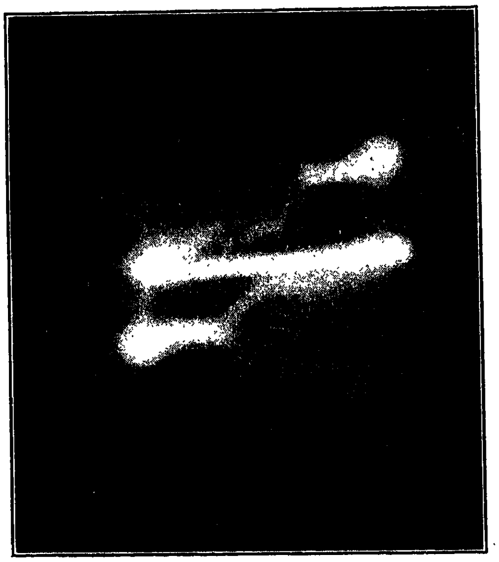
passes on through zero, increases in the reverse direction until the ionization potential is again reached, and the above procedure is repeated.

When the transformer is supplying only one section of neon tube the steady-state output voltage is very low, approaching a short-circuit condition. This is clearly shown in Fig. 10. The current is practically a sine wave in shape and is almost equal in value to the short-circuit current of the transformer.

The load voltage of a transformer supplying first one and then three sections of neon tube as recorded by the low-voltage cathode ray oscillograph is shown in Fig. 11. The waves were drawn out horizontally by a sinusoidal deflector voltage which gives an abscissa scale that is not uniform but follows the sine law. The ordinates are proportional to instantaneous secondary voltage. The original negatives show the oscillations very plainly. These cyclograms were not affected by the measuring circuit and are truly representative of the phenomena.



Load—One neon tube



Load—Three neon tubes

FIG. 11—CATHODE RAY CYCLOGRAMS OF NEON TUBE VOLTAGES

The performance of the tubes when carrying abnormally high currents was studied. Power was supplied by means of a distribution transformer rated at 15 kv-a., 11,500/115-230 volts, 2.4 per cent impedance. Power consumption values as great as 21.9 kw. were obtained with three neon tubes in series. Currents as great as 7.5 amperes (about 240 times normal) were passed through the tubes. The accompanying illumination was very intense and the tubes heated up rapidly. The oscillograph showed the same type of transformer output characteristics as those obtained with the small transformers (Fig. 9). The voltage drop across the tubes was obtained by potential transformer and voltmeter and was found to be approximately 3000 volts for three neon tubes in series carrying 7.5 amperes. Under normal conditions of operation, with approximately 0.031 amperes in the tubes, the voltage drop as determined by sphere-gap and cathode ray oscillograph was substantially the same value.

When a heavy current was passed through the mercury tubes they glowed brilliantly for a few seconds and then began to increase in resistance very rapidly. The power was taken off and after the tube had cooled voltage was again impressed upon them. Full voltage of about 12,000 volts effective was not now sufficient to start complete ionization and produce any appreciable current flow. Probably a sufficient quantity of the gas in the tubes had been driven into the electrodes and glass walls by the violent bombardment to reduce the pressure below the value at which complete ionization would occur at the available voltage.

POWER-FACTOR CORRECTION

The resistance characteristic of gaseous-conductor lamps makes it necessary that they receive their power supply, when operating on alternating current, from a source of high impedance. This is accomplished most satisfactorily from the standpoint of power consumption and current requirement by employing high-voltage transformers having abnormally high leakage reactances. Such a load combination will necessarily draw lagging currents from the supply system.

CORRECTION ON LOW-VOLTAGE SIDE OF TRANSFORMER BY USE OF STATIC CONDENSERS

By the use of static condensers shunted across the low-voltage side of the transformer it is possible to correct the power factor to any desired value. In Table I are given the corrective volt-amperes and the corresponding condenser capacitance required to correct the power factors of the various combinations of tubes to 80, 90, and 100 per cent. It will be noted that a fairly large amount of capacitance is necessary in almost every case and that for any one case the necessary capacitance increases very rapidly as the desired power factor approaches unity.

CORRECTION ON HIGH-VOLTAGE SIDE OF TRANSFORMER

It is possible to improve the power factor of a given combination of transformer and tubes by inserting a high resistance in the high-voltage circuit. The over-all

TABLE I
LOW-VOLTAGE POWER-FACTOR CORRECTION
110.0 Volts, 60 Cycles

Tubes		Power factor (lagging)		Low-voltage correction	
Type	Number in series	Uncorrected	Corrected	Volt-amperes (leading)	Condenser capacitance (microfarads)
Neon	1	0.234	0.800	419.	91 8
"	1	0.234	0.900	452.	99.0
"	1	0.234	1.000	511.	112.1
Mercury	1	0.264	0.800	390.	85.4
"	1	0.264	0.900	426.	93.3
"	1	0.264	1.000	491.	107.5
Neon	2	0.350	0.800	335.	73.3
"	2	0.350	0.900	382.	83.6
"	2	0.350	1.000	466.	102.0
Mercury	2	0.450	0.800	239.	52.3
"	2	0.450	0.900	291.	63.7
"	2	0.450	1.000	385.	84.3
1 –Hg +1 –Ne	2	0.394	0.800	287.	62.8
" "	2	0.394	0.900	336.	73.5
" "	2	0.394	1.000	423.	92.6
Neon	3	0.461	0.800	255.	55.8
"	3	0.461	0.900	313.	68.5
"	3	0.461	1.000	418.	91.6
Mercury	3	0.621	0.800	74.	16.2
"	3	0.621	0.900	113.	24.7
"	3	0.621	1.000	182.	39.8

power consumption is not greatly affected but the illumination is reduced and energy is wasted in the resistance.

Interesting results can be obtained by employing a series condenser in the high-voltage circuit. Table II gives the results of a series of measurements using three neon tubes and various values of series capacitance. The power factor remains high, over a wide range. The power requirement increases with increase in capacitance up to a certain point and then decreases. The tube brilliancy is in this case apparently roughly proportional to the power consumption. For very low values of series capacitance the tubes are unstable at normal voltage because the condensers charge up quickly during each half cycle through the resistance of the tubes and block off the current flow. As a result the illumination persists for only a fraction of each half cycle.

TABLE II
LOW-VOLTAGE CONDITIONS AS AFFECTED BY HIGH-VOLTAGE SERIES CONDENSER
3 Neon Tubes in Series, 110 Volts, 60 Cycles

Low voltage			High-voltage series condenser (microfarads)
Amperes	Watts	Power factor	
1.87	204.	0.990	0.00715
2.21	241.	0.992	0.00813
2.99	329.	1.000	0.01080
3.48	383.	1.000	0.01250
5.29	578.	0.993	0.01730
8.34	862.	0.940	0.02210
10.10	740.	0.664	0.02470
6.76	384.	0.516	0.03260

Table III gives the results of a group of measurements made on various tube combinations with three finite values of series capacitance and with the normal condition which corresponds to infinite series capacitance, for each combination. The three capacitance values were so chosen that they gave power consumption values in the case of the neon tubes approximately equal to, 20 per cent greater, and 20 per cent less than normal. It will be observed that the power factor is slightly over corrected in every case.

Resonant conditions are produced by the series condensers and consequently voltages of abnormal magnitude appear across the high-voltage winding of the transformer and across the condenser. Table IV shows the crest voltages appearing across the various parts of the high-voltage circuit for the different condenser and tube combinations. These voltages were measured by means of a one-inch sphere-gap. The transformer voltages are greatly increased by the series condenser but it will be noted that practically no change occurs in the tube voltage for a given number of tubes of one type.

TABLE III
POWER-FACTOR CORRECTION WITH HIGH-VOLTAGE SERIES CONDENSER
110.0 Volts, 60 Cycles

Tubes		High-voltage series condenser (microfarads)	Low voltage		
Type	Number in series		Current (amperes)	Power (watts)	Power factor
Neon	1	0.00553	1.22	113.	0.842 (Leading)
"	1	0.00652	1.53	138.	0.821 "
"	1	0.00776	1.82	164.	0.820 "
"	1	∞	4.78	123.	0.234 (Lagging)
Mercury	1	0.00553	1.30	126.	0.881 (Leading)
"	1	0.00652	1.56	148.	0.860 "
"	1	0.00776	1.97	183.	0.843 "
"	1	∞	4.62	134.	0.264 (Lagging)
Neon	2	0.00553	1.45	147.	0.924 (Leading)
"	2	0.00652	1.76	177.	0.912 "
"	2	0.00776	2.12	212.	0.910 "
"	2	∞	4.53	174.	0.350 (Lagging)
Mercury	2	0.00553	1.75	185.	0.958 (Leading)
"	2	0.00652	2.03	210.	0.942 "
"	2	0.00776	2.54	264.	0.943 "
"	2	∞	3.92	194.	0.450 (Lagging)
1 –Hg +1 –Ne	2	0.00652	1.91	193.	0.920 (Leading)
1 –Hg +1 –Ne	2	∞	4.18	181.	0.394 (Lagging)
Neon	3	0.00553	1.64	175.	0.972 (Leading)
"	3	0.00652	2.01	210.	0.950 "
"	3	0.00776	2.44	254.	0.948 "
"	3	∞	4.28	217.	0.461 (Lagging)
Mercury	3	0.00553	2.04	220.	0.982 (Leading)
"	3	0.00652	2.46	264.	0.977 "
"	3	0.00776	2.99	321.	0.976 "
"	3	∞	2.11	144.	0.621 (Lagging)

If the series condenser correction were to be employed in practise it would be necessary to insulate the trans-

TABLE IV
CREST VOLTAGES*
110 Volts, 60 Cycles

Tubes		High-voltage series condenser (microfarads)	Crest voltage in kilovolts		
Type	Number in series		Transformer	Series condenser	Tubes
Neon	1	0.00553	....	....	....
"	1	0.00652	23.9	21.8	4.81
"	1	0.00776	....	....	....
"	1	∞	3.82	0	3.82
Mercury	1	0.00553	....	....	....
"	1	0.00652	24.6	21.8	4.25
"	1	0.00776	....	....	....
"	1	∞	3.32	0	3.32
Neon	2	0.00553	27.3	20.5	9.76
"	2	0.00652	25.6	20.8	9.76
"	2	0.00776	27.3	22.2	9.76
"	2	∞	9.76	0	9.76
Mercury	2	0.00553	....	....	....
"	2	0.00652	26.6	21.2	10.2
"	2	0.00776	....	....	....
"	2	∞	8.13	0	8.13
Neon	3	0.00553	25.6	19.1	13.3
"	3	0.00652	27.7	19.1	13.3
"	3	0.00776	29.0	21.2	13.3
"	3	∞	15.3	0	15.3
Mercury	3	0.00553	27.3	18.7	14.3
"	3	0.00652	28.0	19.1	12.0
"	3	0.00776	29.0	20.5	14.3
"	3	∞	12.3	0	12.3

*Crest voltages were measured by means of a one-inch sphere-gap.

formers for approximately twice the high-voltage potentials that at present prevail.

CONCLUSIONS

1. The inherent characteristics of gaseous-conductor lamps are such that when supplied from an a-c. source the transformer must have a high leakage reactance.
2. Because of the combined characteristics of the lamps and supply transformers, the currents drawn have a large lagging component.
3. Power factor is improved by increasing the number of tubes in series or by increasing their resistance.
4. The probable future almost universal use of gaseous-conductor sign lamps will necessitate the use of power-factor correction or the application of special power rates if the use of the high-voltage type lamp is continued.
5. Power-factor correction can be accomplished by the use of parallel capacitance on the low-voltage side of the transformer, or series capacitance in the high-voltage circuit.

ACKNOWLEDGMENTS

The authors wish to express their appreciation of the cooperation of the Electrical Products Corporation, of Portland, Oregon, which supplied the tubes and transformers used in the investigation. Valuable assistance was rendered by J. C. Zancker and Bruce MacGregor.

Discussion

E. A. Loew: I should like to ask the authors whether they have made any careful study to determine what is the most economical ratio of length of tube to applied voltage, for tubes of a given size. In other words, is there an optimum impressed voltage per unit length of tube, other factors remaining constant? It seems to me there is such a relation.

The power factor of an air-blown arc is a function of the voltage. The same is true of the arcs here discussed as shown in Fig. 5 of the paper. If the curves of Fig. 5 were extended to the point where the arc became unstable, my suspicion is that this limiting condition would be found at a power factor of about 71 per cent. At any rate, such is the case with power arcs whose limiting stable operation is found at a power factor of 0.707, as may readily be shown.

The question naturally arises,— is it not possible, and if it is possible, does not good economy demand, that neon tubes and other similar tubes used for sign illumination, be so designed that the voltage applied is properly proportioned to the length and cross section of the tubes, in order that, under normal operating conditions, the power factor will closely approach the maximum value for stable operation?

J. S. Carroll: I should like to enquire as to the possibility of using a third winding on the transformer to which a condenser could be connected for power-factor correction. This would eliminate some of the difficulties encountered with the series condenser and would no doubt be less expensive than using condensers on the low-voltage primary.

N. C. Clark: I wonder if Mr. Starr can tell us how the resistance can be changed by changing the shape or the size of the electrodes at the end.

C. P. Osborne: I am vitally interested in this subject from an operating man's standpoint. Here is a case where the customer is reducing his electric bill by using a small amount of energy and getting a great amount of illumination, but creating a very poor power factor on the system furnishing the service. Why should this additional burden be borne by the power companies when the manufacturer of the sign can install condenser capacity in the signs sufficient to give a reasonable power factor? It is time for the power companies to take a stand in this matter before it is too late.

D. I. Cone: The oscillograms presented with this paper show that in the process of correcting the power factor the action of the tube as a generator of high-frequency harmonics of the fundamental load current has been accentuated. I therefore suggest that in the further study of power-factor corrective apparatus, means shall be included to insure that these harmonics are not fed back into the main power system to aggravate the problems of inductive coordination.

It should be practicable so to arrange the condensers and the inductances in the transformer network as to serve both purposes.

F. O. McMillan: Professor Loew asks if it is not possible to operate high-voltage gaseous-conductor lamps at approximately 70 per cent power factor by either adjusting the tube length to the voltage or the voltage to the tube length. His contention is that from theoretical considerations the maximum power factor is obtained when the resistance and reactance voltage drops in the circuit are equal and the power factor is cosine of 45 deg. This condition is obtained and can be taken advantage of when the reactance and resistance values in the circuit can be adjusted and maintained in a fixed relationship. However, in high-voltage gaseous-conductor lamps the ionization is not sustained from half cycle to half cycle; hence, it is necessary to apply a high ionizing potential each half cycle. This ionizing potential, determined by cathode ray oscillograph and sphere-gap measurements, for the tubes tested was approximately 4.5 times the practically constant voltage required to sustain the current discharge during the remainder of the half cycle after the ionization is established. This condition then requires that approximately 78 per cent of the transformer voltage must be consumed by the leakage reactance of the supply transformer. The maximum possible power factor under these conditions is approximately 62.5 per cent. By actual experiment it was found that the neon tubes began to flicker when the voltage was reduced to a value that gave a power factor of 50 per cent. This is shown by Fig. 5 of the paper in which the curves are discontinued at the flicker value of voltage or the point at which the voltage fails to reach the ionization potential consistently.

The gaseous-conductor lamp then, in its behavior, differs from the power arc because of the fact that ionization is not sustained from half cycle to half cycle during the reversal of current due to the absence of incandescent metallic vapor and hot electrodes capable of electron emission which are always present in the power arc.

In reply to Professor Carroll's question regarding the use of a third winding on the supply transformer for correcting the power factor, we did not do any experimental work using such a transformer. However, such a winding on the primary winding side of the magnetic shunt, designed for a fairly high voltage, would make it possible to use a condenser of smaller capacitance than would be required directly connected to the primary winding and possibly might prove more economical.

In reply to Mr. Clark's inquiry regarding the influence of electrode size and shape upon gaseous-conductor lamp resistance, all of our tests were made with one size and shape of electrode (the type at present used in commercial signs); hence, we have no data on that subject.

Mr. Cone calls attention to the harmonics in the current waves of the two oscillograms shown in Fig. 8 of the paper and states that the neon tube is apparently a generator of high-frequency harmonics and may cause trouble from inductive interference with communication circuits. The high-frequency harmonic current which appears in the current of these two oscillograms is due to a rather bad slot harmonic in the voltage wave of the supply alternator. A filter was used between the alternator and the neon transformer but there was sufficient residual harmonic voltage passing through the filter to cause the observed current harmonic when the high values of corrective capacitance were used.

The Automatic Substation and its Relation to the Electric Distribution System

BY S. J. LISBERGER[1]
Member, A. I. E. E.

INTRODUCTION

SOME 15 years ago in a substation supplying power to an interurban electric railway system, it was demonstrated that electro-mechanical devices could be made to operate the apparatus in the substation so successfully that human attendance might not be necessary. Since that time, the development of these automatic devices has been extremely rapid and, as a result of the progress in this branch of the art, the automatic substation of today has reached a high state of development. The application of these devices to perform and supplant the duties of the human attendant, has been so fascinating that more attention has been called to the automatic substation itself, than to the change that the automatic substation has brought to the distribution system, of which it is an integral part. It might not be amiss to state that the general impression prevails that the automatic substation has its best application in those locations where it will supplant manual attendance; it is true that this reduction in labor expense may be the predominating factor for selecting automatic equipment versus an attended station, but there are other conditions that may affect this choice.

It must be borne in mind that the substation is a definite part of the electric distribution system and that the location of the substation to the distribution network has a most important bearing on the cost of the distribution system. This is particularly important in street railway systems and in metropolitan areas where the load is dense and where better regulation and better service are required as compared to rural communities. In considering the economics of the distribution system, the cost of the substation, the overhead or underground network, the labor of operation and maintenance, the quality of service and the regulation, must all receive their due amount of consideration, as the total costs (capital, operation, and maintenance) are after all the costs that must finally be reckoned with.

It is the desire of the author to point out some of the advantages to be gained by the use of the automatic substation and to discuss in a general way some of the factors which play a most important part in the distribution of the electrical energy to a community. It is, of course, impossible in such an article to do more than discuss the general situation, since there are so many local conditions that affect any solution. Each installation can, therefore, be correctly solved only by a study of the prevailing conditions in the particular territory under consideration.

The automatic substation has been found ideally adapted to the following types of installation.

1. A supply of d-c. energy to urban, metropolitan, and interurban street railway systems.
2. The rural substation supplying only alternating current.
3. On consumer's premises where a special substation is necessary and where the customer's requirements may call for either or both alternating or direct current.
4. In supplying energy to a 220-volt d-c. Edison network in a metropolitan community of not excessive size.
5. In metropolitan areas where one or more types of service may be supplied from the same substation.

The latter may involve a combination of several of the above types. There are perhaps several other classes that might be added, such as automatic operation of synchronous condensers at isolated points and such as a semi-automatic installation in a large station. This condition assumes that the station has a large number of units and that switching conditions require an attendant. In such a station, it is probable that complete automatic operation is not advisable, yet partial automatic operation may reduce operating expense and give better service than a complete manually operated station.

In the study of the distribution system, of which the automatic substation may be a part, the first consideration that enters the study is that of the control or type of automatic equipment that is to be installed and here again the automatic substation may be subdivided into several classes, the most important of which are:

1. Complete or partial supervisory control from an adjacent station or location.
2. Indication (without supervision) at a distant point as to the performance of the apparatus in the automatic station.
3. The complete automatic substation without control or indication at any adjacent station or location.

Distant indication or control is obtained today largely by means of a wire circuit, but it is to be noted that the "carrier" system will undoubtedly be used successfully in the future.

In making a selection of any one of the above types, it is necessary to have a full understanding, not only of the operating performance involved in the particular situation, but also a full knowledge of how the several types of automatic installations perform under varying conditions. Those organizations or individuals, who

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have operated only manual substations when considering the application of the automatic substation, always have in mind what might happen with automatic equipment and due to inexperience with automatic equipment, it is likely that they will either overdo the installation of automatic devices or select an equipment which is much more expensive and complicated than conditions justify. It must not be forgotten that even in manually operated stations things do happen, that the operators do make mistakes, and the mere fact that there is always a man there, does not always insure as good operation as with automatic devices.

It is today generally recognized that for certain installations the automatic equipment can be made more foolproof than manually operated and that in certain types of installations, the automatic equipment will restore service faster than the attended equipment. It is further known that the automatic devices will protect the apparatus better than the keenest operator and will start and stop the machines, lock out the feeders, etc., with more accuracy and certainty than when the similar operations are performed by the hand of man. It is therefore necessary to understand clearly what automatic equipment will do before making a selection of the type of control desired.

Assume for a moment a medium size system, wherein one or more automatic stations are equipped with supervisory control, the control point being an adjacent substation. If such a system is to be operated on the orders of a central load dispatcher and if the control station must obtain orders from the load dispatcher before carrying out any switching operations in the automatic substation, it is probable that better service will develop if the automatic substation be of the fully automatic type rather than supervisory, as in times of trouble or if faults develop, the fully automatic substation will eliminate the defective equipment and will restore service faster than if supervised. If the control station for the automatic be one where the operator is likely to be very busy, in the event of system trouble, then the automatic station will deliver better service if it be not of the supervisory control type. However, there is always a feeling on the part of the operating man, in which feeling he is justified, that some one should know what is going on in the automatic substation, as apparatus may lock out and nothing will be known of it, either until the customer complains or until the routine inspection takes place. Such operation may cause a serious impairment in the service. Hence, a combination of automatic and indication at some distant point may be found to be the ideal solution, as the equipment will take care of itself during times of trouble on the system or locally and at the same time some one knows whether the station is functioning satisfactorily or not. If there are to be several substations and if they are not too far apart, the remote indications becomes all the more necessary, as with several substations the investment in the indicating equipment will be justified in view of the possibility of reduced inspection and maintenance costs.

The above statements have reference largely to substations in the metropolitan areas. It is not believed that such installations are necessary in rural substations located some distance from the nearest community, where said indications would be uneconomical. The selection of a particular type for the purpose at hand, must consider not only the question of what type of service it is desired to give, but also the economics of the situation, and it likewise involves a question of judgment.

SUPPLY OF POWER TO URBAN AND INTERURBAN RAILWAY SYSTEMS

In installations of this type, the automatic substation finds its ideal application. Certainly in both metropolitan and interurban communities there is the opportunity for a large reduction in the amount of feeder copper necessary, with an attendant improvement in voltage regulation if the substations can be economically spaced and located. In interurban systems, the substation capacity is not large and in many cases there may be only one equipment necessary and in the majority of cases rarely over two equipments in any one substation installation, all of which tends to simplify both the installation and operation, as well as reduce the capital cost. Where more than two machine equipments are necessary, the present development of the automatic apparatus is somewhat complicated owing to the number of combinations introduced by the addition of the third (or fourth) machines.

If conditions are such that more than two machines are necessary, it is possible that some form of supervisory control equipment may be simpler and less costly in both installation and operation. This statement is particularly true if remote control indication is desired, since the control or indicating circuit would be existent and the addition of supervisory control would, therefore, not be a costly addition. It must not be overlooked that the installed cost of the automatic equipment for a railway machine with a reasonable number of feeders, represents an expenditure of approximately 30 per cent of the cost of the machine itself and that the cost of this equipment does not materially change with the size of the machine, if sizes between 500- and 2000-kv-a. units are considered. It is therefore desirable on any given system to use as large equipments as are economically possible, not only to reduce the number of units, the size of the building, the number of switching elements, etc., but in order to obtain simpler operation. In selecting the number of substations and the size of the units, the relation of the location of the substation to the railway system must of course be considered, and, likewise, the cost of the power supply to the substation will enter the economic problem. All of these factors must be properly balanced for the best solution.

In the automatic substation supplying power to a railway system, load resistors, high-speed circuit breakers, temperature relays, and similar equipment provide better protection to the machine and to the equipment than that equipment ordinarily installed where it is manually attended and where such devices are not absolutely necessary. The use of the high-speed circuit breaker and its reclosing equipment gives better service than that manually operated, as these equipments automatically reclose the circuit the instant that the trouble disappears, a thing not accomplished with a manual attendant. When system faults occur and several substations are shut down, the automatic equipments invariably restore service faster than those manually operated. From my observation, automatic operation is certainly to be preferred to manual for this type of service.

From a service standpoint, even in the substation where there may be an attendant, the automatic equipment is preferred, even though it may not be economically justified, in view of the fact that some attendance at the station is necessary for other purposes. In those substations in metropolitan communities where the load is very heavy and more than three equipments are necessary, it is doubtful if any form of automatic substation will be economical, although where traffic is very dense, some automatic substations can very probably be located as an economical means of feeding the distribution network under peak load conditions, provided, of course, that the cost of real estate and the power supply extension does not make such a station uneconomical.

The above statements apply entirely to motor-generator and rotary equipments supplying power to railway systems. It is entirely possible that the mercury arc rectifier in the future may change some of the conditions that have been outlined above. There is no question but that the rectifier has some material advantages over rotating apparatus and it is entirely possible that some of the difficulties will be ironed out in the future. This is a development that must be watched and one that may permit the economical feeding of a railway network from a larger number of separate substation units than is now regarded as advisable.

Rural Substations, Isolated Consumers, and Special Synchronous Condenser Installations

These installations may be classed as being of the same type, in so far as the application of automatic devices are concerned. They are exceedingly simple and offer no special problem.

The rural substation prior to the development of the automatic art was unattended in the majority of cases. Fuses and oil circuit breakers gave some protection to the lines and equipment. If a circuit was interrupted, it remained out of service until the consumers complained or until inspection revealed the trouble. The introduction of the automatic devices has materially bettered the service with only a slight increase in cost. The outages, due to line troubles, have been materially decreased by the automatic reclosing breaker as troubles often clear themselves on the first opening and service is resumed as soon as the breaker is reclosed.

To both the isolated consumer and rural substation it is possible to give a most reliable type of service if two supply lines feed the substation, as the present day automatic devices effect a quick transfer of the load from one circuit to the other in the event of interruption and will even transfer the load back to the preferred circuit if desired. To those classes of consumers that require an isolated d-c. supply, such as mines and similar specialized industries, the development of automatic equipment has made it possible to supply these industries with most satisfactory service at a cost that would have been otherwise prohibitive. The automatic equipment in this type of installation will certainly render better service and the apparatus will be better protected than with manual operation, bearing in mind that the type of operator normally obtainable for this class of service is not particularly intelligent and the type of service required in many cases could hardly be supplied without some supervision.

The application of the automatic principle to the isolated synchronous condenser station located at the most advantageous point on the system for power-factor and voltage correction has made such installations economically justifiable since the substation does not require any attendant or housing facilities for him. Proper location for this type of installation means a reduction in the capital investment that would otherwise be necessary, either to provide proper regulation or suitable power-factor correction elsewhere on the system.

The type of equipment now available for this installation will perform its duties as well as the human attendant, if not better.

In all of the above types of substations, with the possible exception of the synchronous condenser station, supervisory control or remote control indication is hardly needed or justified, and therefore a full automatic substation finds its ideal application in these cases. In so far as the synchronous condenser station is concerned, the only advantage of remote control indication will be to inform the distant control station of what is happening in the substation. The question as to what expense is justified in having this added feature is one that can be answered only after a study of the local conditions that pertain.

With the most satisfactory performance of the automatic substation, it is now possible to locate such facilities at the most advantageous point on the distribution system. This means a reduction in the length of feeders, better regulation, and, particularly in rural communities, cuts down the length of individual feeders so that in the event of line trouble a large territory is not out of service at one time. Such rural substations occupy only a small amount of ground space, and, as the apparatus can be housed either in steel cells or be made completely outdoor, such construction is not expensive, it being possible to build such a substation, including land and regulators, for a cost not to exceed $15.00 per kv-a. if the load is of the order of 3000 kw. and the supply and distribution voltages 11 and 4 kv. respectively. Such installations materially reduce the cost of the secondary network and certainly provide better service than if a large territory were supplied from one substation feeding a very large area.

SUPPLY OF ENERGY TO A 220-VOLT D-C. EDISON NETWORK

Many communities in this country with a population of more than 400,000 people have in the past been furnished with 220-volt d-c. Edison service in the congested areas. Such service was originally supplied for all purposes in this congested area, but of late there has been a tendency to reduce the area in which this type of service has been supplied and to supply in its stead alternating current. Some utilities have even gone so far as to supplant the Edison service entirely with a-c. supply. However, as there are many buildings that have large installations of d-c. equipment, it is necessary in such cases to supply some d-c. service or else to provide some conversion apparatus located on the consumers' premises to give the service required. Whether this conversion apparatus should be supplied in duplicate is a question that again must be determined by knowing local conditions.

Why should the d-c. supply be abandoned in favor of an a-c. supply? Many of the d-c. systems were originally built with storage battery standby. As the load grew, it became necessary either to increase the existing station with its battery facilities or else to establish other stations, some of which may have had stand-by batteries. With one or more substations, the network, which is largely underground, was tied together with junction boxes and fuses and the system operated as a network. If there were no batteries or if the batteries were not large enough to carry the system even at reduced voltage during times of system trouble, there was always the difficulty as to how service would be restored on the Edison network during times of system trouble. Such a d-c. network requires a large amount of copper and a larger number of ducts. The capital investment and the operating expense for such a system, particularly if batteries were required, are greater than for an a-c. system of equal capacity.

With these general factors in mind, it is not difficult to see why the a-c. system is to be preferred. Yet on the other hand there is nothing simpler to operate than a d-c. Edison network, and maintenance costs for the underground system are not high. If a new system were to be built today, it is doubtful if the d-c. system would be installed, and yet where such systems are installed with the changed conditions brought about by the automatic substation it is likewise doubtful if an a-c. supply should be selected to supplant the existing d-c. system. With the newer types of motor-generators with load limiting and similar characteristics and with the automatic devices now available and in service, and if the d-c. system can be fed from a number of substations with not more than two units per substation, a very economical and high quality of service can be rendered: the d-c. system can be operated as a network with a material reduction in the length of feeders, number of ducts, and consequent savings in losses and investment, and without storage batteries,—the automatic equipment restoring service most satisfactorily in the event of trouble. It is not intended to imply that automatic equipment in a system of this type is the equal of manual stations with storage batteries, nor is it intended to imply that, in extremely large metropolitan areas where the density of load is very heavy, the automatic substation can supplant the manual substation entirely, as the number and size of the machine equipments necessary in a given substation may require such a complicated and costly outlay that the installation would not be justified, but where the load is not too dense and where a number of substations can be ideally located, and particularly if a main and auxiliary bus are not necessary, the automatic equipment as applied to this form of supply is certainly worth careful consideration as against a change to an a-c. supply with its attendant difficulties. An a-c. supply to deliver service equal to that of direct current under such conditions should be operated as a network. Also, such a type of supply means large transformer vaults, with some problems of ventilation, network protectors, etc. Certain consumers will still demand some d-c. supply, for which there must be some form of conversion apparatus.

It is not always possible, owing to crowded street conditions, to find ample space for the necessary a-c. facilities, and when one considers the growing density of load, with the street obstructions, the cost of equipment necessary to provide an a-c. network and the changes in the service and metering equipment that are necessary, to say nothing of the write-off involved in abandoning the existing system, the newer application of the automatic substation with its d-c. network is worthy of careful consideration. It is to be particularly noted that the cost of real estate, extension of supply feeders, and the possible future density of the territory will require a careful consideration of this problem, and it is entirely possible that even though the service be overlapping in a given area, some direct current, rather than a complete change, will be the economical solution.

If such d-c. automatic substations are used, there again enters the question of the type of station—whether it shall be full automatic or supervisory, or a combination of the two. As the distances between substations will not be great and as there will be rotating apparatus installed, and as the service demanded must be of an excellent character, it is probable that some form of supervisory control will be most advisable. Such a control system will be essential if there be more than two machines in a given substation, as the complications introduced by the addition of the third machine do not make for a simple layout. In any event, the cost of either full supervisory or partial control will hardly be a controlling factor in the solution of this problem, as the added expense of such equipment will be very nominal, particularly where there are several substations; and as there will be a reduction in inspection and maintenance expense, a supervisory system of some type will most probably be warranted.

With such a control system, it is reasonable to suppose that even in the large metropolitan area with dense loads that a small number of automatic substations may find an ideal application in the economic solution of the supply of the territory in question.

AUTOMATIC SUBSTATIONS IN METROPOLITAN AREAS

In large metropolitan areas the use of the automatic substation vs. the attended station requires more careful consideration than in any other situation, as there are many things that affect the problem, such as the several classes of service that may have to be supplied out of one station, the density of load, the cost of the supply lines to the substation, the cost of real estate and building, and the question of fire risk.

If the utility is to supply several classes of service, such as power to a street railway system, d-c. Edison service for a limited area, a-c. service for industrial purposes, and if there is street lighting, all to be supplied out of the same station, it is most probable that the variety of service and the amount of apparatus that must be installed can best be served from an attended substation. With such an installation, the application of partial automatic operation, such as reclosing feeders on the a-c. system, automatic operation of all station auxiliaries, automatic starting of motor-generators or rotaries for the railway system, will be justified as it will reduce the number of required attendants and at the same time better service will be given.

However, outside of the congested areas, such as in the industrial and residential territories where only railway and a-c. service are demanded, it is quite possible that the automatic substation will be best suited for meeting the additional load growth.

It may be found that the existing substation facilities cannot be readily increased, due to limited real estate, particularly where the adjoining property is covered with substantial structures and where the cost of reconstruction of the existing facilities to provide increased capacity will be quite high. In such cases, particularly in the older parts of the city, there will be crowded street conditions where the cost of obtaining additional output facilities will likewise be expensive. Under such conditions the automatic substation as an adjunct to the existing station may be the ideal solution for meeting the additional growth, particularly if the amount of load on the new substation will be a minimum of 4000 to 5000 kv-a.

In such territory, it is most probable that the supply lines to the new substation must be underground, and as the cost of such underground supply lines is a large percentage of the cost of the additional facilities, sufficient load must be available if an economical installation is to be had.

Where the generating capacity is of such an order that the use of oil switches of high rupture capacity is necessary, it will be found that switching costs at the substation are also a factor in the cost of the total development. In order to reduce the cost per kv-a. of switching and underground lines, supply cables must be of such a size that they will carry loads of approximately 7000 kv-a., this assuming that the voltage of the supply system is approximately 12,000 volts, and in addition to this it is possible to eliminate the switching at the substation end by treating the cable and transformer bank at the substation as a unit, thus not only saving the cost of switches, switchboard, etc., but also the building space required for them. The automatic station lends itself particularly well to this type of design if a spare cable and transformer bank unit are installed, the banks feeding the secondary bus through oil switches, the secondary bus in turn being arranged in units with a given number of feeders per bank; the secondary bus sections so arranged that they can be tied together through oil switches. In the event of a failure of a cable or bank unit, the main secondary oil switches on the bank open, the secondary bus tie switches close, and the other bank takes the load. Such an installation can be made with two or more banks and cable units, it being necessary that the bank and cable unit have some spare capacity in order to take the load of the adjoining section.

Such an installation requires no switches on the high-voltage side, the minimum number of relays, is without the complications of high-tension switching, and it is most probable that it would work cheaper than any other installation if the costs of switching and building are of serious moment in any other type of design. Such an installation will function faster in times of trouble than could be done by any manual attendant, and it is probable that such an installation, if the feeders were equipped with reclosing devices, would hardly need any form of supervisory or remote indication except to ease the mind of the operating man.

If the conditions of service require that railway load be supplied in addition to alternating current, it is possible that some high-tension switching will be necessary, particularly if the railway load requires such capacity that the converting apparatus cannot be economically fed from the low-voltage bus, and for the reason that there is always some diversity between the railway load and the general lighting and power load. The most economical installation will be had by supplying both loads from the same supply cables. In such an installation it is most probable that some form of supervisory equipment will be advisable, particularly if the number of feeders for the a-c. system is large and if it is found necessary to keep a check on what is going on in the railway part of the installation.

There is a variety of arrangements that can be had which will deliver a high degree of service without supervisory control, but supervisory control should not be regarded as prohibitive in cost, for if duct line space is readily available and the substation located approximately 3½ mi. from the control point, the supervisory system, including the control cable, should not cost more than $1.00 per kw., if the substation is of the order of 10,000 kv-a.; this is certainly not an unreasonable sum.

In the choice of any system of control, it should be realized that the full automatic apparatus will clear the trouble and restore service faster than can be done with supervisory equipment or with a manual attendant, and it will relieve the distant operator from any duties, particularly if that operator has other duties that will require his attention during time of system trouble; and furthermore if the system be operated under dispatcher's orders whereby the operator must get orders from the dispatcher before closing the line, certainly the full automatic is to be preferred to the supervisory control for the reasons as given above. It seems best, therefore, that the system be one in which the apparatus functions automatically without human attendance, and that when necessary, as a check and in order to save inspection trips, etc., that supervisory or remote control indication be superimposed in order that some knowledge may be had on how the apparatus is functioning.

There is, I think, one further advantage in the full automatic apparatus in that trouble as a rule can be more easily located than if the equipment be controlled from a supervisory system for if trouble on a machine or line develops, the protective devices will open the circuit, perhaps lock it out, but at any event will usually clear the fault. If the station must be visited to ascertain the cause of trouble, the fault should be more readily located with the full automatic type as there are more relays which have a definite function to perform, and if the inspector is familiar with the apparatus it is often much quicker to locate the trouble by observing the position of the key relays rather than have to run down the trouble step by step which is necessary when the supervisory system is used, as this system uses less relays and thereby more nearly approaches the conditions that pertain when the station is manually attended.

In passing, it might be well to mention the subject of street lighting in connection with automatic substations. While it is entirely possible to control constant current transformers by time switches, supervisory control, etc., there are certain disadvantages in the use of these transformers such as the required building space, the large number of outgoing wires, and the inconvenience caused when a series circuit opens, as it is likely to cover quite a street area. Automatic apparatus can be had which will open and close the circuit normally and protect the circuit in times of trouble. This may require the use of quite a few auxiliary devices.

The experience of the writer on the system with which he is connected has demonstrated that there is a material saving and improved service in the use of the pole type constant-current transformer, said transformer being fed from the multiple 4-kv. circuit (which circuit is combined in part with the regular feeder system) and said transformers feeding small groups of series circuits. These transformers are usually about 20 to 30 kv-a. capacity each.

The primary street lighting circuits are controlled either by time-clock or supervisory control, or they can be controlled from a distant point by carrier at very nominal expense.

The multiple circuit occupies a substation space equivalent only to one feeder position. This circuit can supply 800 lamps, and if some cascading is used the number can be increased to 1000 without difficulty.

It may be possible to eliminate entirely the street lighting equipment from an automatic substation by supplying said lighting from other substations. This is particularly true if "carrier" control is to be used. The only point to be brought out in the above discussion is that the the street lighting installation is extremely simple and offers no special problem in the design of the substation.

REMOTE LOAD INDICATION AND OTHER METERING EQUIPMENTS

If the distribution network is fed by a number of substations and if the feeders are or can be tied together through sectionalizing switches, it is often desirable to know the load that the several units in the automatic substations are carrying; this is all the more important if the station is supervisory controlled, as the control station must be in a position to know when to put in and take out the supply units. The necessity for remote load indication equipment depends, in a large measure, upon the detail design of the system. If, for example, the cable and transformer bank are a unit and this unit feeds a group of low-voltage feeders, a fair idea of the load can be had from the reading of the ammeters at the feeding point, and if all the supply cables emanate from the same station, remote metering is hardly necessary. On the other hand, if there are several units fed from the same supply cable, load conditions are not so readily known. During times of system disturbance, a substation may have to take a heavy overload and it is often desirable to know just what is going on in the automatic substation under such conditions, as it is not always possible to send an inspector to the substation when the system is upset.

If there are communication wires between the control point and the substation for supervisory control, the added expense of remote load indication equipment is not excessive if a large number of readings is not desired. The cable type for direct indication of remote load indication is not satisfactory for distances in excess of approximately 2½ mi.

Remote load indication equipment in the present state of development cannot be regarded as entirely satisfactory, although it can be reasonably expected that improvements will be made in time. It would, therefore, appear advisable at present to install only such equipment as is felt will be absolutely necessary. Most stations have a fairly well defined load characteristic and after this is determined a fair amount of information can be had from the supply line readings if the operator is carefully instructed.

There does appear to be some room for improvement in the lower price recording meters for automatic substation work. As the station will be visited only at periodic intervals, it is necessary to have recording instruments that will register, with a reasonable degree of accuracy, the desired record for at least seven days. If charts must be changed any oftener, it becomes a burden. If the regulators are equipped with indicators that register the maximum boost positions, a fair idea can be had of feeder performance. During the peak period of the year, it may be advisable to take a few readings rather than go to the expense of equipping every feeder with a recording ammeter.

The entire instrument equipment should receive careful attention as there normally is no one present to read the instruments and only those instruments that have to be read at intervals or are used in test should be installed.

There is a definite need for a reliable thermometer that will register the maximum temperature on apparatus such as transformers and regulators, the present curve drawing types being too large and expensive.

SUBSTATION DESIGN

The design of the automatic substation is somewhat different from the attended substation. The most important elements to be noted are:

1. The design of the building if apparatus must be housed, or design of the structures if it is to be outdoor.
2. Ventilation in the case of housed equipment.
3. Fire risk.
4. Economical arrangement of the apparatus, particularly with relation to the building structure, and with the interconnected devices.
5. Arrangement and grouping of the apparatus to facilitate quick inspection, and location of faults.

Building Design. If the substation is to be located in a residential area, special treatment must be accorded the building to make it harmonize with the surrounding property. It must be architecturally attractive, should very probably be not over two stories high, and must be of such construction that if the apparatus located therein be noisy, such noise must be confined to the building. Where only static apparatus is housed, such as transformers and induction regulators, noise is not much of a problem, but where rotating machines are used, the elimination of the noise requires much more care in building design.

In a noiseproof station, it will be necessary to provide some form of double walls; that is, an outside wall with intervening air space between it and the inside wall, the latter being of plaster or similar material. In place of the double wall, it is possible to use sound absorbing materials such as celotex and plaster, or in lieu thereof, hollow tile with a felt and plaster covering. There are various materials that can be effectively employed so as to eliminate entirely the noise going through the wall. It will be found advisable to eliminate all windows and skylights and reduce the number of doors to a minimum. If the doors must be of sufficient size to admit large machines, it will be difficult to make this door noiseproof unless special precautions are taken. It will be found advantageous to use a heavy door of wood construction and then to place a removable covering over this door, such covering being placed on the inside of the station, and built of soundproof materials. It must be bolted tight against the main door frame. The smaller entrance door should either be through a vestibule having two doors, or there must be two doors of a construction similar to the main door. All cracks around the doors must be absolutely tight as small cracks offer a passageway for a large amount of sound.

The foundations of the machines and the supports for contactors should be kept separate from the main building structure. It will be found advisable to mount such apparatus as induction regulators on cork pads.

If the transformers be located outside of the building and there are no motor-generators or rotaries in the building, it will probably be unnecessary to provide forced ventilation. As a matter of fact, in cold weather it may be necessary to provide some method of heating the building. However, motor-generators, etc., will require forced ventilation of the building.

The air entrances and exits must be properly baffled, otherwise they will become passages for the exit of noise. It is probable that in a residential area, all wires leading to and from the station will have to be underground for at least a limited distance. If the station contains several classes of apparatus located in separate rooms, it may be necessary to build only one part noiseproof, the static apparatus not causing sufficient noise to require the extra precaution and expense necessary with rotating machinery.

If real estate conditions permit sufficient width of building to allow for easy movement of machines, and if they do not exceed 1500 kw. in size, it will be found advisable to build such building without a crane. This not only reduces the height of the building, but materially reduces the cost.

If the station is to be located in an industrial or rural area, the above precautions may not be necessary and it may even be desirable in the case of static apparatus that all of such apparatus be entirely outdoor type, thus eliminating the building. However, some modification of the conventional outdoor design may be found advantageous, such as the use of steel cells to house oil switches, instrument transformers, disconnecting switches, etc. As the substation will be unattended, therefore, not under the care of an operator, everything should be done to eliminate the possibility of outside interference, such as kite strings, birds, small boys, etc. Where outdoor structures with exposed conductors and switches are used, greater clearances are necessary, as faults have developed from birds and animals grounding the conductors to the structure. These conditions require clearances which sometimes produce a rather large structure. Furthermore, some form of housing is necessary for instruments, relays, etc.

A very economical design has been worked out, wherein all wires are brought to the substation underground, such wires terminating in a steel cell which houses the oil switch, instrument transformers, disconnecting switches, switchboard instruments, etc. All leads to the transformers and regulators are wiped in. This type of design has a decided advantage in that there is not an exposed wire in the installation. Indoor equipment (which is cheaper than outdoor and incidentally more easily obtained) can be used. The oil switch, instruments, control relays, etc., are grouped close together, requiring extremely short interconnecting leads, thus reducing expense. Bypass switches (air type) are provided in the cell to allow for inspection of the oil switch. Such a station supplied at 12 kv. and distributing energy at 4 kv., if of 3000 kv-a. and above, can be built at a cost of $15.00 per kw., which price includes three single-phase induction regulators per feeder. (For complete details of such a station, see article by R. C. Powell in *Electric World,* Feb. 26, 1927, Vol. 89, p. 449.)

Ventilation. If ventilation is required, it presents no difficult problem; it is only an added expense. It will be found advisable to install some type of air-cleaning equipment in order to reduce the quantity of dust and dirt brought into the station. Such equipments are now obtainable in the form of dry filters so arranged that said units can be quickly cleaned without taking the apparatus apart, in fact can be made automatic cleaning. The installation will be found justified by the reduced cleaning and maintenance that would otherwise be necessary.

These filters cannot be relied upon to decrease passsage of noise, and if noise is to be eliminated it will be necessary to provide baffles or mufflers, both in entering and leaving air passages. The type of ventilating installation may require the use of either forced or exhaust fans, or both. If the substation is under supervisory control and if the load has a definite daily characteristic, the fans can be controlled from the supervising station after the temperature characteristics of the station are known. The use of thermostats for starting and stopping fans is very satisfactory and quite reliable, and low in first cost. The layout of the ventilating systems requires some careful thought and study; several schemes can be used, that is, sufficient air can be discharged into the room to keep the temperature of the room in the vicinity of the machines at the proper point, or the duct system can be so arranged that air is dicharged into a pit under the machines or from ports at the side of and adjacent to the machines. It is often difficult to provide a duct system that is reasonable in cost, due to space limitations, and under such conditions it might be advisable to discharge a larger amount of air into the room and do the cooling a little less efficiently.

Two installations, designed by the writer, which have been in operation for more than two years, have shown the effectiveness of discharging the air into the room in the vicinity of the machine, rather than using a costly duct system to convey the air under the machine. The standard machine of today draws in the air at the ends and in a direction parallel to the shaft. Therefore, if air enters the pit under the machine, it must find its way to the ends of the machine; hence the effectiveness of the air discharged into the room in the vicinity of the machine. If there is a number of induction regulators installed with barrier partitions, only sufficient air is required to keep the air moving to prevent dead pockets and hot spots.

If the transformers are located inside of the building, some ventilation will be required, the amount and type depending largely upon the size of the transformers and their location.

Double walls or similar construction to prevent noise introduces an effective insulation which decreases the radiation of heat through the building walls. Due consideration must be taken of this condition when designing the ventilating system, as well as the fact that the automatic substation is usually smaller than an attended substation.

The building should be of fireproof type.

Fire Risk. The question of fire risk has received perhaps the least attention and yet it is one of the most important considerations. While electric fires are few in number, they do occur, and if it happens in an unattended station, considerable damage may result before anything is known of the accident.

It is therefore most desirable to locate transformers out of doors, if this can be done. It may be necessary to house them in a separate building or part of the substation; it is entirely probable that they can be located outdoors in such a way as not to be unsightly, particularly if they are protected by a wall or screen of proper design. In the event such transformers are located outside, it is advisable to have all connecting leads wiped in rather than have exposed bushings, see Fig. 1.

Oil switches should be in compartments with barriers arranged to prevent the spread of fire and the flow of oil in the event a tank bursts, (Fig. 2). Induction regulators cases should be of strong construction, preferably the boiler plate type, and there should be proper barriers between each group, a small pit or oil dam being provided for each set. If there are high-tension switches, it will be advisable to locate them in a part of the building isolated from the other apparatus, and should there be any large number of switches or regulators, it may be advisable to erect partitions which will provide a number of small rooms instead of one large open space. Such partitions are not difficult or costly to install. The location of the apparatus with reference to adjoining apparatus, wiring on the switchboard, etc., should receive most careful consideration.

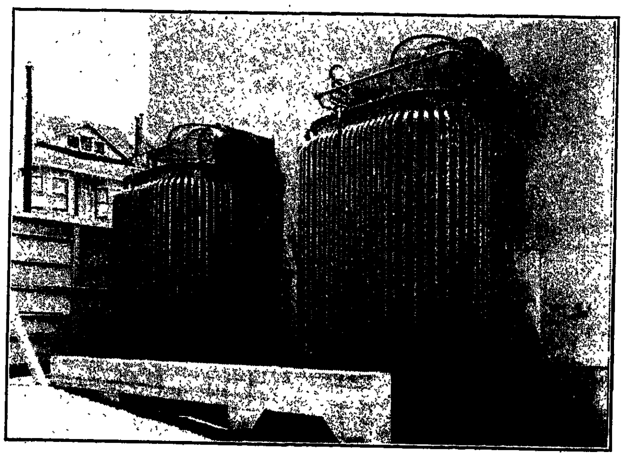

Fig. 1—Three-Phase, 11-Kv., 1500-Kw. Transformers

Note the wiped-in high-voltage leads. Secondary leads are housed in a copper box. These leads enter the building in a protected box

If a fire should occur, it is of course most necessary to have the ventilating fans stop. This can be done by locating fusible links at critical parts of the room (which parts would be the first to get hot) the links so arranged that they will open the control circuit of the ventilating fan; and if the substation be supervisory or the indicating type, the opening of such circuits could be registered at the control point.

In a railway station, there is always the possibility of the bus becoming grounded and the machines will then feed into the short circuit until the load limiting resistors commence to function through the operation of the temperature relays. This short circuit might start a serious fire if the apparatus is not properly spaced. It is possible to insulate the switchboard and its supports and then ground the frame through a grounding relay, which will trip all d-c. feeders and machines, thus clearing the bus. This type of protection, while very effective against the bus grounding, may cause a total interruption if some of the auxiliary devices ground, particularly if the grounding relay is not set high enough. It is a question of the choice of two evils.

As there is always the chance of a regulator breaking down and of oil being thrown out of the case, this might result in a serious fire. As a fault in the regulator usually goes to ground, it is possible to protect, in part, against this hazard by insulating the regulator cases from the ground and then grounding the cases through a grounding relay. In the event of a failure of the regulator, the operation of the grounding relay locks out the circuit so that the reclosing devices do not allow the feeder switch to be thrown in again. This device is very reasonable in cost and it has been found to be an excellent protection.

If the substation be a large one, the question of fire risk should receive careful attention. It is the one case, perhaps, where the human attendant may be relied upon better than the automatic devices, unless it is proposed to equip the station with some form of fire protection which will shut off the sources of supply and flood the station or room with a gas that will quench the fire. Such installations are possible, but perhaps not advisable from an operating or cost standpoint.

Arrangement of Apparatus with Relation to the Building Structure, and Grouping to Facilitate Quick Inspection. The designer of the station must consider both of the above features when laying out the station, as it is essential that an economical arrangement be had and at the same time it is equally essential that the apparatus be so grouped that trouble can be readily located if and when it develops. There are really two separate ideas,

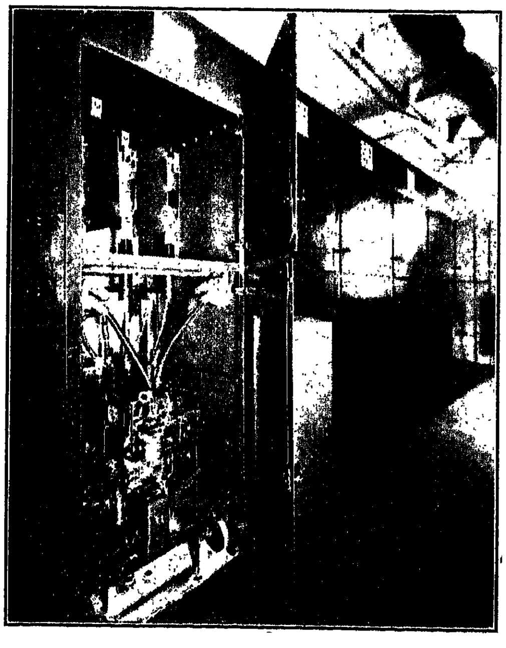

Fig. 2—11-Kv. Switches in Steel Compartments

A simple roll-out type of switch is used requiring less space than the truck type. Control connections are made through flexible couplings which are, in actuality, combined in the final design, but each must be borne in mind when planning the job.

The additional auxiliary apparatus necessary in an automatic substation requires more room than that ordinarily required in the attended station, and as there are many devices which will interconnect and interlock, a careful study of the physical layout is necessary to produce an economical installation. In railway substations in particular, the switchboard room required is several times that of the non-automatic; the heavy duty resistors, high-speed circuit breakers, circuit interrupters, etc., also require additional space and as these various pieces of apparatus must be interconnected, it is essential that the grouping be carefully studied.

The transformers, machines, and the auxiliary devices will cost a certain sum and this cost is a constant irrespective of the arrangement of the apparatus. If the location of the various units is not studied carefully, it is surprising what sums can be spent for interconnecting cables, buses, conduits, and control leads; it will be found that the building costs will also be higher if these features are not well worked out. Where rotary converters are used, the placing of the transformers outside of the main building, as previously mentioned, has distinct advantages in reducing the cost of the building and ventilation. Such transformers should be located as close to the machines as possible, in order to reduce the length of the secondary leads. The high-speed circuit breakers when on the negative side of the machine should be as close to the machine as possible and adjacent to their complementary resistors; the machine and breakers can be treated as a unit because all this equipment must be out of service if it is desired to do any work on any part of the unit. If these devices are not located close to the machine, long runs of heavy cable and control leads are necessary. An example of how this apparatus may be grouped and made a part of the unit is shown in Fig. 3.

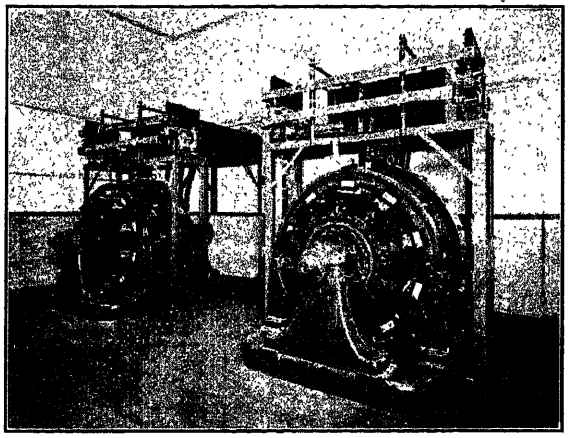

FIG. 3—TWO 1500-KW. 600-VOLT CONVERTERS

Note short leads from the machine to the two high-speed circuit breakers on negative side. The metal boxes overhead enclose the secondary leads from transformer

As the load limiting resistors are quite large and are likely to get quite hot, they should be located well overhead where the heat is easily dissipated and yet as close to the bus as possible, in order to reduce the heavy copper runs necessary; there are devices that are interlocked with the feeder breakers and they should likewise be close to them to reduce the control runs. The contactors used with the load limiting resistors should be located so that the arcs will not travel in a direction where damage may occur and they should be well above the floor line so as to prevent the arc's blowing in the face of a passer-by. Where heavy arcs are likely to occur, extra spacing and barriers should be provided to confine them effectually. Where fuses are used on 600-volt potential or control circuits, the cartridge should be enclosed in a non-conducting fire resisting box; this is particularly necessary on the back of switchboards where the failure of a fuse to function properly is likely to cause serious destruction to the adjacent wires. The detail wiring of the railway switchboard should be given most careful consideration, as there is a large number of wires carrying several voltages, both alternating current and direct current, on the back of the board and it is essential that the spacings be ample, lest a fault on one communicate trouble to the others, which may render all the protective apparatus inoperative.

The standard size of railway boards where high-speed breakers or circuit interrupters are used, has been a 90 in. high by 20 in. wide panel, on which panel it has been customary to mount all of the apparatus except the high-speed breaker, this device being mounted on a supporting frame at the top and to the rear of the face of the panel. It is necessary to have two disconnecting switches for isolating the breaker or interrupter to do maintenance work. Such an arrangement takes but little space, but has a decided disadvantage of crowding too much apparatus on one panel, allowing insufficient spacing for relays, fuses, etc. and, furthermore, producing a very congested mass of wiring on the back of the panel. Severe burnouts have taken place, particularly when a 600-volt piece of apparatus, such as a relay, goes bad. The congested condition on the back of the switchboard is worthy of attention, as there are control wires of several voltage classes, heavy busses, and interconnecting leads, all crowded into a very close space, rendering it somewhat hazardous to do maintenance work and resulting in rather bad burnouts if faults occur. If the panel is widened, it makes the switchboard rather long, yet it does not materially assist in relieving the congested wiring condition on the back of the board.

In order to overcome these objectionable features, it may be found advisable to arrange the switchboard in two sections, back to back, the machine relays and instrument equipments, the feeder equipments such as the relays, and circuit interrupters being on the front of the board, and on the board to the rear, there are placed the disconnecting switches and such relay and metering equipment as it is not essential to have on the front of the board, (Fig. 4). This arrangement has several decided advantages. It makes it possible to reduce the length of the building, but more important, it allows the placing of the heavy bus in a position well above the other apparatus, thus making it easy to connect the bus to the breakers or circuit interrupters and the disconnecting switches, and at the same time leaves the backs of the boards clear of heavy copper, which, under the older type of installation, makes it extremely difficult to get at or change incidental wiring on the rear of the panels.

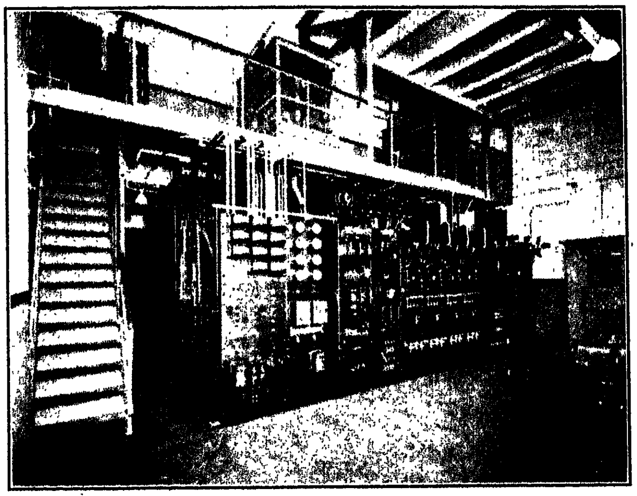

Fig. 4—Front of Switchboard

Contains 11-kv. control panels, automatic equipment for two machine control, and four feeder circuit breakers. Note the load-limiting resistors on the gallery

The interconnecting and interlocking control leads, of which there are quite a few, can be carried in metal troughs or conduits between the two boards, thus allowing for easy interconnection to the several devices. It will be found advisable where there are several classes of control wires, to carry each voltage class of wires in separate conduits rather than mingle the several classes in one conduit, as this makes it very easy to shoot trouble and further provides some additional safety in case one of the wires grounds. A general view of such a type of installation is shown in Fig. 5.

These are details that seem hardly worthy of mention, yet if a detailed examination of some installations is made, it will be found that the above features are most important in obtaining economy in the first cost, and safety and speed in maintenance work. It should be borne in mind that where there is no attendant in the station, it is not always known just what happens and when the inspector arrives on the job, it is essential that the arrangement be such that he can readily find the trouble without having to resort largely to a cut-and-try method of isolating the component parts of the several circuits.

It is essential that careful attention be paid to the seemingly small details, for experience shows that more faults occur from the small apparatus than from the major parts of the equipment. Many relays and auxiliary devices are necessary, particularly with d-c. apparatus, and these relays should be carefully marked and lettered. Of course, the operating man must have a thorough knowledge of the equipment as the position of the relays will often be a guide in informing him as to just what piece of apparatus has functioned and much delay in rectifying trouble can be saved if he will observe the position of the relay, that is, if it is out of its normal position, such as being closed when it should be open or vice versa. Particular care should be taken with the lettering and symbol marking of the switchboard wiring and equipment.

CONCLUSION

The automatic substation has been developed to a high degree of perfection. It can be relied upon to deliver an excellent type of service, particularly if proper precautions are taken in the design and installation: in fact, in certain cases it will deliver better service than that given from an attended station. Careful inspection and maintenance will prevent much trouble.

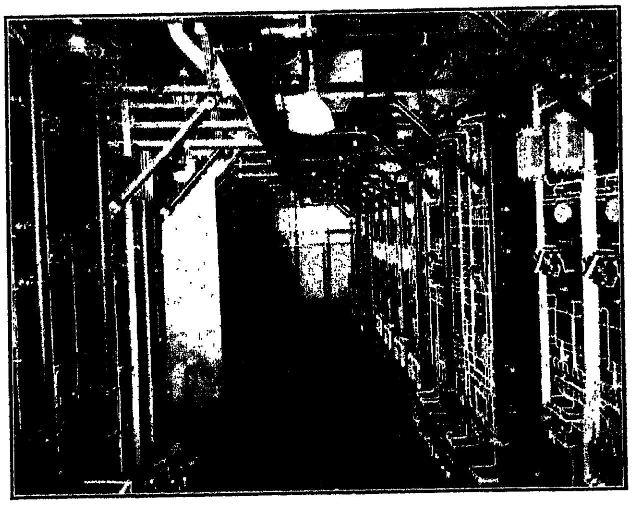

Fig. 5—View Between Front and Rear Switchboards

Note the absence of heavy copper runs on back of panels. Metal trough overhead is divided into three compartments with removable sections on sides. Note ease with which the interconnecting leads are taken out of this box to various control panels. Barriers on left are between the d-c. feeder panels

This development has provided the means for locating the supply station at those points in the distribution network where previously such a station would not have been possible, and as a result large economies in the distribution network can often be effected by the application of the automatic substation, but to make this possible it is essential that the substation investment should not overbalance the saving to be effected in the distribution system. The cost of the supply lines, real estate, and buildings often determines the economic solution, as the cost of much of the apparatus is almost a constant no matter where it is located on the system.

The type of control should receive most careful consideration, particularly if the station is not of extraordinarily large capacity.

With careful design, proper spacings, and isolation of apparatus, the fire risk can be reduced to a minimum.

Further development of the apparatus and control systems and careful attention to the schematic design of unattended stations and its connected system will produce, in the future, even greater economies (with improved service) in the distribution of electrical energy, than are apparent today.

Discussion

M. T. Crawford: The Puget Sound Power & Light Co. provides automatic substations not only in city residential areas, but in a number of suburban and rural districts. In the city, the substations are of the full automatic type and the amount of load handled warrants the installation of the best and most modern equipment available.

A different economic problem presents itself, however, in the case of a substation to supply a suburban or rural community where a load of only a few hundred kilowatts is involved. If this load is largely suburban homes and farms, it may represent three to five thousand consumers. The high degree of electric range saturation on our company's system, the large number of water heaters, electric brooders, and other domestic appliances, has brought us to face a situation where an interruption of thirty minutes may cause great public inconvenience and impair both public relations and sales. It has, therefore, become rapidly very important to safeguard against interruptions on this class of service, and yet at the same time the highest economy is essential.

Our present practise for this service usually consists of an installation of three transformers up to 200 kw. maximum size each, on a two- or four-pole structure, transforming from the 13-kv. local transmission line down to 2 kv. or 4 kv. for distribution purposes. These voltages are in the more closely built areas where farms consist of only a few acres each of rich soil, or in suburban residential sections near the city. In the outlying regions, where the load is more scattered, high distribution voltages are employed.

We have equipped a number of these pole-type transforming stations with automatic switching on both primary and secondary side. On the 13-kv. side, two pole-top sectionalizing switches of standard type are installed, connecting the transformer bank to either of two 13-kv. supply lines. Automatic operation is provided which switches the load over from the preferred to the auxiliary supply line in case of a power failure on the preferred line.

On the 2-kv. side, induction regulators are installed for voltage regulation and crossarm-mounted oil switches are provided for outgoing feeders and equipped with automatic reclosing devices. The automatic equipment on these installations is of a comparatively inexpensive type and the general class of construction is also of a very modest character. The total cost runs around $12,000 for a 600-kw. installation with three regulated lighting feeders and one unregulated power feeder, including automatic equipment. It is true that the cost per kw. is no less than a high-class full automatic substation in the city where built for large capacity; however, this cost per kw. would be very much higher if a high class installation were put in for only 600 kw. In other words, for a modest total investment, a substation can be built in suburban territory which will have automatic features for protecting the service and which will be entirely adequate for a period of five to ten years while territory is developing. If it assumes urban proportion at the end of that time, a permanent high-class substation can be built and the less expensive equipment readily moved farther out to newer territory.

The problem of a-c. or d-c. service in congested areas of large cities has to be settled on a basis of the economics of the local situation, as the author points out. In Seattle the older d-c. system was paralleled by an a-c. network with interleaved feeders and automatic network switch protection. This was done eight years ago, and although the d-c. system has been kept up with full battery protection, and for a number of years past no effort has been made to require customers to take a-c. service rather than d-c., nevertheless the a-c. load has grown very rapidly and the d-c. load has just held its own, due to customer preferences. A certain amount of d-c. service is required, however, to meet public needs fully. The automatic substation described by the author, installed in moderate sized units on customer premises, admirably meets this need in new territory where no older d-c. system exists.

The need for remote load-indication equipment is very acute in some situations where there is no well defined load characteristic at various hours of the day, such as trunk-line railway electrifications. We hope soon to have equipment perfected for trial installation which will give a totalized indication at one point of three large blocks of power at different locations, the maximum single distance being 120 mi. We now have satisfactory carrier telephony over this route via 110-kv. lines, and there seems to be no reason why carrier impulse indications cannot be transmitted for remote metering purposes.

C. E. Carey: I had hoped the paper would bring out the economic relation of the number of small automatic substations and inherent low feeder losses as compared to the large manually operated substation and high feeder losses. Somewhere between these extremes there is an economic balance and that economic balance bears a very important relation to the distribution system.

The automatic substation places in the hands of the operating men a system of high-voltage transmission and low-voltage distribution. It places in their hands a system of a-c. transmission and d-c. distribution which is quite similar to that used for a-c. systems. The automatic substation is as reliable as any piece of apparatus we have, whether it is a-c. or d-c. This fact has been recognized on the large suburban and interurban electrifications which have made use of the automatic substation which not only reduced the operating cost but also increased reliability of service.

The problem of applying automatic substations to a distribution system resolves itself into an economic study. The economic study is the same as any other engineering economic problem, namely the balancing of the fixed charges against the operating expenses. Restating that problem means to find the lowest annual operating expense for a given combination. This would be my attack and method of applying automatic stations to any distribution system.

I should like to discuss the question of fire hazard mentioned in Mr. Lisberger's paper. One of the developments to reduce this hazard is the inertaire transformer, in which an inert gas has replaced the oxygen in and above the oil.

Mr. Lisberger states that induction regulators should be made with boiler-plate tanks so as to confine any explosion within the induction regulator in its case. This does not seem to me to be the true answer. When you consider the enormous energy released at the time of a secondary explosion you find that the thickness of the boiler-plate tank must approach more nearly an armor plate. We have provided regulator tanks with corrugations so designed that they will expand in case of explosion. Actual tests by the use of controlled bombs have shown that the corrugated tank will withstand explosions which rip open the boiler-plate tanks.

L. R. Gamble: In reading Mr. Lisberger's paper, I noted particularly his discussion of the use of the automatic d-c. substations for supplanting the present tendency to use a-c. networks. It seems that it is always the question of economics which must be considered in the final analysis, although the public must not be forgotten. Their demands must be supplied.

I feel that in a few years from now direct current will be quite a relic. People are demanding more and more the a-c. service, and why? It is a question of maintenance with them because the a-c. motor does not require nearly the maintenance that a d-c. motor requires, and as a result, the demand is for a-c. service and the power companies are going to supply it.

Analyses made in Spokane, and on other systems would indicate that the annual charges for an a-c. network run from 15 to 25 per cent lower than those for a d-c. network. With these points in view, it seems that the direct current will be a thing of the past in a few more years.

Chester Litchtenberg: A vision of important electric system changes is disclosed in this paper. A radical step in the design of distribution systems is discussed.

One feature makes it difficult to establish broad standards for automatic-station application at this time. It is the embryonic state of the automatic station art. Combined with this is a period of rapid development. For example, remote load-indicating equipment is just now being developed to a point where successful application is practicable. This extension of the automatic station art is sure to make for a broader field together with a more intensive use of the equipment.

The recent development of less expensive curve-drawing instruments is just being announced. These will make it possible to record information on circuit conditions as they occur in automatic stations. It will also make possible less frequent visits to these stations for the purposes of obtaining records. Moreover, they will permit less voluminous records to be kept. Those records too will be more accurate than those usually available.

Automatic switching equipment with its extensions into supervisory control and telemetering now forms the nucleus for radical revisions in the art of generating, transmitting, and distributing electric power. As these new developments become more familiar to electrical engineers, greater economies in operation will result.

P. B. Garrett: Mr. Lisberger has drawn certain general conclusions which do not seem entirely justified in view of the fact that the experience in question has been limited in some cases to certain types of equipment only, and does not cover all such equipments available for the applications outlined.

Mr. Lisberger states that remote load-indication equipment in the present state of development cannot be regarded as entirely satisfactory. It should be noted that a number of large operating companies in other sections of the country have experienced very satisfactory operation of remote metering equipments of other types over a period of several years.

Experience and tests have demonstrated the ability of the corrugated welded steel tank of induction feeder regulators to withstand shock from internal explosions. Mr. Lisberger's paper would tend to indicate greater strength in the boiler-plate type.

As Mr. Lisberger states in his paper, location of the high-speed breakers on the negative side of the machine does make it very desirable to locate them as close to the machines as possible. However, when the high-speed breaker is inserted in the positive lead, which is equally as desirable, it is often found convenient to mount it above and to the rear of the switchboard. No extra lengths of cable and control leads are necessary in this case since the positive cable is normally carried to the switchboard.

Mr. Lisberger lays considerable stress on the matter of speed in maintenance work. It should be noted that with the type of equipment which allows for annunciation of any or all causes of shutdown, it is not necessary to resort to a cut-and-try method of isolating the component parts of the several circuits. Due to the location of certain relays, such as grid thermal relays, and also due to the necessity of removing the covers of certain types of relays to observe their physical position, much delay in rectifying trouble can be eliminated by the use of annunciators grouped in a single relay, which tell the cause of shutdown at a glance.

Mr. Lisberger's outline of the application of distributed automatic substations to supply an existing Edison network offers interesting possibilities of improved service. Such a scheme eliminates the cost of a changeover to an a-c. network but does not result in a saving in operating expenses comparable to the a-c. network. Independent studies made by several operating companies agree that the best type of a-c. network is not more than half as expensive in total annual charges as a corresponding d-c. network.

A-c. network systems are being operated, installed, or planned in a large number of cities, large and small, in all parts of the country. In such a system, all of the secondary mains in the area are tied solidly together to form a grid of conductors to which all customers are connected. This grid is fed by a considerable number of transformer banks which are connected to several independent primary feeders and located in vaults or manholes throughout the area. This renders the space requirement of the individual transformer vault comparatively small. The dependability of the Edison d-c. network and the economy and efficiency of the a-c. method of distribution using high-voltage feeders and transformer banks at the points of utilization are provided by the a-c. low-voltage network.

J. Hellenthal: I should like to touch on the automatic substation as applied to congested load centers. For our city loads we use fully automatic substations which give fully automatic control of supply lines, full protection for the transformer banks, and fully automatic protection to the feeders. We have found in five years' experience that the automatic substations are very economical from the standpoints of design and operation. In the design of the station we have to take into consideration various factors, the most economical grouping of equipment, the proper construction of the building to forestall fire hazards and to obtain minimum insurance rates.

We find that in the a-c. automatic stations, we get considerable variation in costs per kv-a. In the costs we include not only our buildings, our equipment, but also our land and the feeder run to the cable terminal pole. In our original designs we ran into costs that went up to $28 and $50 per kv-a. installed capacity. By giving considerably more study to our designs, we have reduced these costs dependent upon the size of the stations. For instance we have one station with the present installed capacity of 9000 kv-a., with sufficient building and structural facilities to double that capacity. With the present capacity our total cost is $25.09 per kv-a. When this station has been developed to its ultimate capacity our cost will have been reduced to $12.04 per kv-a.

This station is a modern fireproof building with decorative features, in the heart of a residential area, with ample shrubbery and everything about it to make it a very attractive building.

In our other designs we have gone to a more compact station, built upon a unit principle, where so many feet of building will provide for a certain number of incoming lines, transformers, and feeders. As our demands increase we add another unit to the building. This type of station we have developed to 6000 kv-a. installed capacity for $18.55 per kv-a. When increased to 9000 kv-a., which is the ultimate capacity of the one unit, this cost will be reduced to $16.74. We feel this is a very representative cost and is very economical.

We maintain a rigid inspection of our substations. At present we have five full automatic substations with a total kv-a. capacity of about 32,000, with provision for more than double this on the existing premises. In addition we have quite a number of industrial stations that are semi-automatic.

We have an inspector on duty at all times. He is provided with a car. The inspector must visit each station on each shift, giving twenty-four hours' service. This facilitates precluding any misoperation, and gives an opportunity to check up on his records to see what feeders and transformers are doing, and assists in much quicker restoration of service after a feeder has been locked out.

A. P. Sessions: Mr. Kellogg touched on automatic notification of switches tripping out in automatic stations. In the Southern California Edison Company we have found a very effective way of doing this by the use of our telephone lines, using the telegraph-type relay.

We have what we call switching centers or grouped supervision of our stations. These outlying automatic substations will report to the switching center. While the only indications we get is that something needs attention, it is always within a few miles of a switching center from which an electrician may be sent as soon as the switches trip out the third time. It is a very cheap way of getting results, of course, assuming you already have the telephone lines.

Caesar Antoniono: (communicated after adjournment) There is one phase of the automatic substation application on urban and interurban railway systems that should be more fully emphasized, an item of major importance in that class of service and that is the possible mitigation of electrolysis by the proper spacing and location of the substations as suggested, thus reducing the capital investment which would be necessary under certain conditions to prevent damage to underground structures.

The Electrolytic Zinc Plant of the Sullivan Mining Company

BY ELLERY R. FOSDICK[1]
Associate, A. I. E. E.

Synopsis.—This paper describes the recently constructed electrolytic zinc plant of the Sullivan Mining Company which is located near Kellogg, Idaho. The first unit which has just been completed has a capacity of 50 tons of slab zinc per day. Provision has been made for two additional units which will bring the capacity up to 150 tons per day.

The "Tainton-Pring" electrolytic process, which uses strong acid for leaching and high current density for electrolysis, is employed in this plant.

The metallurgical process and the physical layout of the plant are briefly described, after which follows a general discussion of the electrical features.

GENERAL

The Sullivan Mining Company is owned jointly by the Bunker Hill Sullivan Mining and Concentrating Company and the Hecla Mining Company. It owns the Star Mine located near Mullan, Idaho. This mine is connected, by means of an 8900-ft. cross-cut, with the 2000-ft. level of the Hecla Mining Company's shaft. A complex silver, lead, zinc ore is mined in the Star ground, trammed through the cross-cut, raised through the Hecla shaft, and is then shipped to a concentrating mill at Kellogg. The zinc concentrate from this mill is then taken a distance of one mile to the electrolytic zinc plant. Zinc concentrate from sources other than the Star Mine will also be treated, this being a custom plant which will afford an outlet for the refractory and complex zinc ores of the Coeur d'Alene district. Construction on the first unit was started in August, 1926 and practically completed by August, 1928.

The erection of this plant is the result of much experimental work in developing a method of treatment for these ores. The plant has a nominal capacity of 50 tons of slab zinc per day but provision has been made for additional units to increase the capacity to about 150 tons daily.

METALLURGY

The Sullivan Plant employs the "Tainton-Pring" electrolytic process, which is based on the use of strong acid in leaching and of high current density in the electrolysis. The acid strength is about 28 per cent and current density about 100 amperes per sq. ft.

Concentrate. Briefly outlined the process is as follows: Zinc concentrate is roasted and the roasted calcine is magnetically separated into two parts, (1) a magnetic portion, containing most of the iron and the zinc ferrite which is formed in roasting the ore, and (2) the non-magnetic part, containing practically all zinc oxide.

Leaching. The magnetic portion containing the zinc which is not readily soluble is added to the hot, strong 28 per cent acid which attacks and dissolves the zinc compounds. The oxide portion is then added to this pulp to neutralize the unconsumed acid and to precipitate iron and other impurities which have also been dissolved by the acid.

Purification. The pulp is then filtered. After being dried the residue, containing the lead and silver which was in the original zinc concentrate, is shipped to the Bunker Hill smelter for the recovery of these metals. The zinc solution is agitated with metallic zinc to precipitate cadmium, copper, and cobalt. It is then filtered again after which the neutral zinc sulphate solution goes to the electrolytic cells.

Electrolysis. The electrolytic cells operate at an acid range between 22 and 28 per cent sulphuric acid. When the acid reaches the upper limit, a portion of the solution is withdrawn from the cell solution circuit and a corresponding volume of neutral zinc sulphate solution is added. This reduces the acid strength to the lower limit. The strong acid which is withdrawn is used in the leaching of the calcine as previously described. The process is thus cyclic.

The heat developed in the electrolysis raises the temperature of the electrolyte. This therefore is circulated through coolers consisting of lead-lined boxes in which are placed lead pipe coils through which cold water is flowing. The flow of warm electrolyte is counter current to that of the cooling water in the coils. The electrolyte after being cooled returns to the cells in continuous circuit.

ARRANGEMENT OF GENERATOR BUILDING, CELL ROOM, AND SUBSTATION

Geographical Location. The site of the new electrolytic zinc plant is in a canyon known as Government Gulch near Kellogg, Idaho. The buildings of the electrolytic zinc plant are placed upon the east slope of the gulch. See Figs. 1, 2, and 3 for the general layout. This is an advantageous location, for most of the solutions can flow by gravity from the higher buildings down through the various processes to the cell room, thus reducing the number of solution pumps to a minimum. A further advantage of the location

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is taken by placing the stack upon a saddle of the east side of the gulch about 200 ft. above the highest building of the plant.

Buildings. The main building in which the metallurgical processes are carried on is 216 ft. long and 305 ft. wide. The generator building is 57 ft. wide and 54 ft. long and the electrolytic cell building is 57 ft. wide and 271 ft. long.

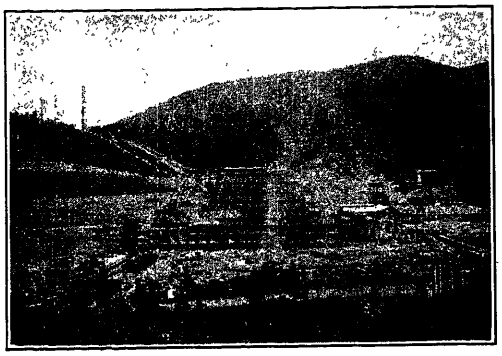

Fig. 1—General View of Electrolytic Zinc Plant

All footings and substructures are constructed of concrete designed for 3000 lb. strength. The coarse aggregate used consisted of tailings from the Bunker Hill & Sullivan Mill.

The buildings are steel frame structures with the walls made of wood girt studs on which was stretched wire netting. Concrete was then sprayed on the netting against forms placed on the outside of the wall, in this way forming concrete panels and concrete covered studs. The result is a type of wall called gunnite.

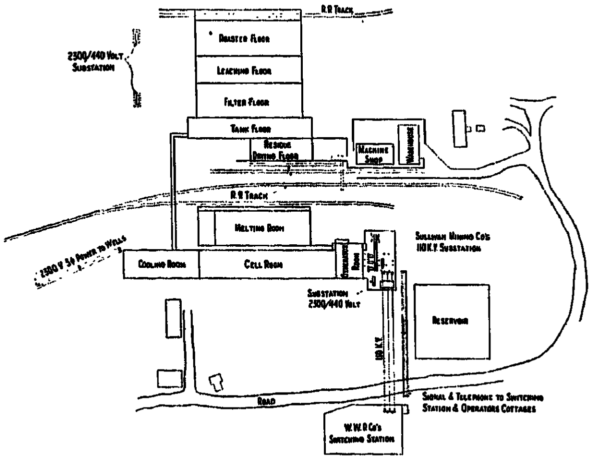

Fig. 2—General Layout of Electrolytic Zinc Plant

The roofs of the buildings were built up of 2 by 4 in. timbers placed on edge and side by side over the steel trusses. Waterproof roofing material was laid upon this surface.

Fully 25 per cent of the wall space of all the buildings is occupied by windows. The large amount of window space together with white ceilings gives very satisfactory daylight working conditions. Artificial illumination with an average intensity of 6 foot candles is provided in both the generator building and the cell room, while in other parts of the plant it is of somewhat lower intensity but is ample for the work to be done.

Substations. The generator building is located at the south end of the cell room, and immediately adjacent to this building is the Sullivan Mining Company's 110-kv. outdoor substation. Opposite the Sullivan Mining Company's substation on the west side of the gulch is the Washington Water Power Company's 110-kv. outdoor switching station.

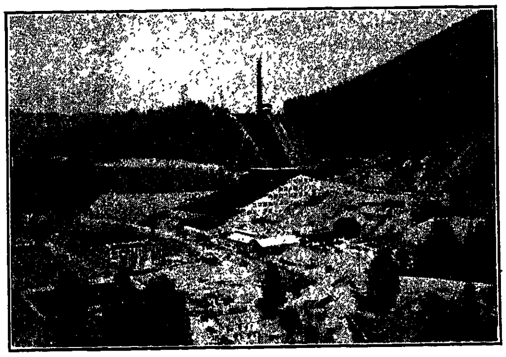

Fig. 3—Another View of Electrolytic Zinc Plant Showing Power Plant

Equipment. In the generator building there is a main floor and a basement. The synchronous motor-generator set bases are resting on the main floor. Machine foundations extend down to footings below the basement floor. The walls of the machine foundations have openings for ventilating louvers.

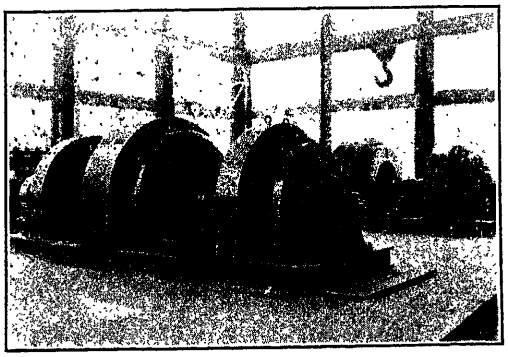

Fig. 4—Synchronous Motor-Generator Sets

The main control board is at right angles to the shafts of the two machines, and is located on the main floor. See Fig. 4.

A 2300-volt three-phase bus and switching structure is located in the basement directly below the main control board. Here the synchronous motor-generator, starting, running, and compensator oil circuit breakers are mounted with their accessory equipment.

On the opposite side of the basement, and in line with the copper busses from the generators to the electrolytic cells in the cell room, is the 500-volt d-c. switching equipment.

All conduit runs were kept in the concrete forming the floors and walls of the generator building. It was desired to keep the basement free from exposed conduit because of the large amount of bus copper to go in, and also to reduce to a minimum any windage losses in ventilation. Numerous junction boxes and pull boxes were provided to facilitate future changes and extensions of station control wiring.

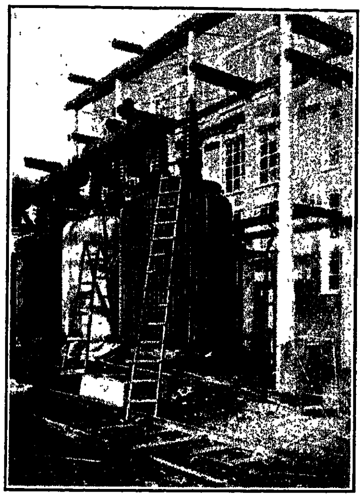

Fig. 5—110-Kv. Outdoor Transformers

The air washer and blower equipment for the motor-generator sets is at one end of the basement placed beside, and discharging toward Unit No. 1 foundation.

Each generator and each synchronous motor has a motor driven remote controlled field rheostat mounted on the side of the machine foundation.

Direct current for oil circuit breaker operation, signals, and emergency lighting in the cell room and generator room is supplied by a 60-cell Exide type E-11 storage battery located in a separate room in the basement of the generator building.

The generator room is equipped with a 25-ton Whiting crane having the travels operated manually by means of endless chains but with the hoist motor driven.

SUBSTATIONS

Power Supply. Two transmission lines feed the Washington Water Power Company's switching station, one being a 110-kv. transmission line from the East Side Substation at Spokane and the other a 60-kv. line from the Post Falls Generating Plant. The 60-kv. line is connected through a 15,000-kv-a. transformer bank to the 110-kv. line. Continuity of service is further insured by a third line operating at 110 kv. extending from this switching station through the larger substations of the Coeur d'Alene Mining District and joining at a point near Burke, Idaho, the 110-kv. line from the Montana Power Company's Thompson Falls Plant.

Substation Equipment. The Sullivan Mining Company's Substation has a 10,000-kv-a. transformer bank protected by an oxide film lightning arrester and a 110-kv. oil circuit breaker. The transformers are 110k-v. to 2300-volt, oil insulated, self-cooled, delta-delta connected. See Fig. 5.

Power Cables. Twenty-three hundred volt three-phase power enters the generator building through four 750,000-cir. mil, three-phase lead-covered cables connected in parallel. These cables connect to the 2300-volt indoor switching structure to which the two synchronous motors and five 2300-volt plant feeders are connected through oil switches. See Fig. 6.

Plant Feeders. Three of the 2300-volt plant feeders terminate in smaller outdoor substations where the voltage is stepped down by transformers for 440-volt, three-phase power and 110-volt lighting. One of the 2300-volt feeders supplies power to the 2300-volt, three-phase well pump motors located at the wells in the Coeur d'Alene River Valley about one mile away, the other feeder supplies 2300-volt, three-phase power to the pumps for circulating the electrolytic cell solution.

SYNCHRONOUS MOTOR-GENERATOR SETS

Choice of Generating Equipment. After carefully considering the demand to be made upon them and the reliability of the source of power, two three-unit synchronous motor-generator sets were chosen to supply direct current to the electrolytic cells. Although their efficiency is somewhat lower it was thought best to use synchronous motor-generator sets instead of booster synchronous converters. The following are some of the advantages that favor synchronous motor-generator sets for this particular installation.

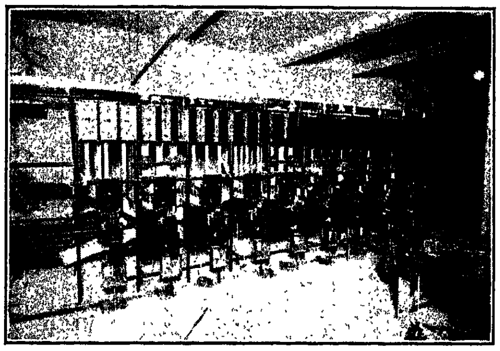

Fig. 6—2300-Volt Indoor Switching Structure

1. They are more stable, not being affected to such a great extent by surges in the long transmission lines.
2. It is easier to attain automatic regulation with them for they require fewer automatic features.
3. They have a wider range of voltage.
4. They will correct the power factor of the total plant load.

5. Only one 110-kv. transformer bank and one 110-kv. oil circuit breaker with the accessory equipment are needed. A synchronous converter producing 500 volts d-c. would not operate at a voltage on the alternating current side which would be suitable for power distribution about the plant. It would, therefore, be necessary to have a second 110-kv. transformer bank for this service when using synchronous converters.

Synchronous Motor-Generator Sets. The synchronous motor-generator sets are of General Electric Company manufacture and supply the current for each electrolytic cell unit of 150 cells. The normal output is 8000 amperes d-c. at 500 volts. The synchronous motor of the generating unit is rated at 4400 kv-a., 2300 volts, speed 514 rev. per min. On each end of the motor shaft is a 4000-ampere, 500-volt shunt wound d-c. generator. A direct connected exciter supplies field current for both the synchronous motor and d-c. generators.

The following tables give the efficiencies of the synchronous motor-generator sets and transformers:

Power factor	Synchronous motor-generators			Per cent maximum current load for one min.
	Full load	¾ load	½ load	
1.0	92	91.3	89.0	150

110-kv. transformers

Power factor	Full load	¾ load	½ load
1.0	99.0	99.05	98.95

Including transformer losses, the synchronous motor-generator sets have an efficiency of 91.0 per cent when operating at full load.

The motors are started on low voltage obtained from a compensator and after getting up to speed are connected to the 2300-volt bus. A voltage relay gives the desired sequence interlock between the starting and running oil circuit breakers.

D-c. Busses The copper busses connecting the generators to the electrolytic cells are quite long. The current flowing in them is approximately 8000 amperes and does not vary more than 4 per cent up or down. It was, therefore, necessary to study heating losses carefully in these busses. As a result of these studies, two curves were plotted, one using cost per year for each foot of bus with a 20-year life, 10 per cent scrap value, and 6 per cent interest on investment, and the other using cost of power loss per year for each foot of bus based upon the cost of power when the machine and transformer losses were included. Each of these cost curves was plotted cost against cross-section of the bus in square inches. The intersection of the two curves indicated quite clearly the most economical size of bus to use, which is 15 sq. in. cross-section for 8000 amperes or a current density of 533 amperes per sq. in.

Direct current is carried from each generator to the circuit opening devices by five bars ¼ by 6 in. copper. In each generator positive bus is a 6000-ampere, 650-volt d-c. air circuit breaker. Each negative bus has two 3000-ampere, 500-volt knife switches connected in parallel. After passing through the circuit opening devices, the two negative busses and the two positive busses each combine to form a bus of ten bars of ¼ by 6 in. copper. These carry the 8000 amperes of direct current to the electrolytic cells in the cell room. The total amount of bus copper used for carrying the current to the electrolytic cells weighs 61,700 lb.

When the plant is expanded to five units of generating equipment a transfer bus will be used. Unit No. 5 will be for stand-by service and can be used in place of any unit by means of the transfer bus.

Automatic Regulation. The cyclic variation in the conductivity of the electrolyte, taken in conjunction with periodic shut-downs of electrical apparatus for cleaning, oiling, and brush attendance, made it imperative to adopt some means for obtaining constant kw. input to the synchronous motors in order to maintain the desired load factor. Automatic regulating equipment for this purpose was furnished by the General Electric Company, and regulation is obtained in the following manner:

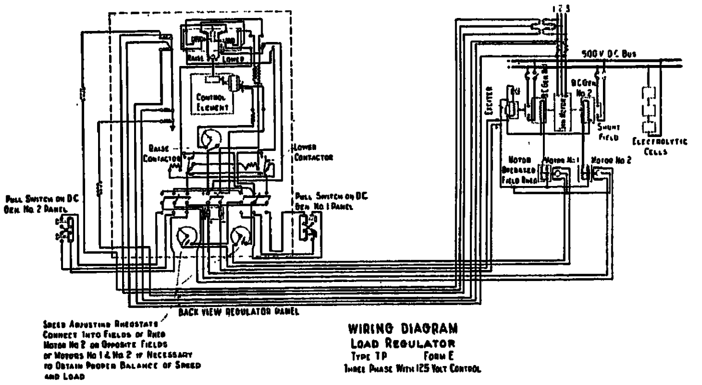
Raise
Lower
Control Element
Raise Contactor
Lower Contactor
Pull Switch on DC Gen No 2 Panel
Pull Switch on DC Gen No 1 Panel
Back View Regulator Panel
Speed Adjusting Rheostats Connect Into Fields of Rheo Motor No 2 or Opposite Fields of Motors No 1 & No 2 if Necessary to Obtain Proper Balance of Speed and Load
1 2 3
500 V DC Bus
Exciter
DC Gen No 1
Syn Motor
DC Gen No 2
Shunt Field
Electrolytic Cells
Motor Operated Field Rheo
Motor No 1
Motor No 2
Wiring Diagram
Load Regulator
Type TP Form E
Three Phase With 125 Volt Control

Fig. 7—Rear View of Switchboard ÐWirin Diagram

Current transformers and potential transformers in the 2300-volt power cables to the synchronous motors of the motor-generator sets (see Fig. 7 for wiring diagram) have their secondaries connected to the control element, or contact making wattmeter of the automatic regulator which is mounted on a control panel of the main switchboard. This control element through a timing device, closes one of two pairs of contacts at regular intervals, or does not permit either of them to close, until some fluctuation in load causes a change in power taken by the synchronous motor. When a pair of contacts close they complete a circuit, by means of an auxiliary contactor, through the field rheostat head driving motors of both generators. The driving motor circuits closed, cause the driving motors to rotate the field rheostat brusharms. This regulates the field current so as to change the generator loads, either increasing or decreasing them as needed, and so changes the power taken by the synchronous motor.

Machine Ventilation. In considering the ventilation of the synchronous motor-generator sets, the usual problem of washing and cooling air was encountered and, in addition to this, it was necessary to make sure that no air was sent through the machines without first going through the air washers.

The gases that leave the stack will have a large amount of sulphur dioxide in them; being readily soluble this combines with atmospheric moisture to form sulphurous acid. Even though the top of the stack is in a favorable air current and some 500 ft. above the generator room, it may happen that some of this sulphur dioxide and sulphurous acid will be present in the air taken in for machine ventilation. There is also the ventilating air from the cell room which at times may contain a mixture of dilute sulphuric acid and zinc sulphate solution, which may also be in the air supplied to the machines. Hence, it was thought advisable to wash the air thoroughly to remove both of these and any sulphurous acid that may be present.

A semi-enclosed system of machine ventilation was installed. The generator building itself is used as the enclosure around the machines. Enough cool air is drawn in from outside the building to keep the temperature of the air being drawn in through the washers down to approximately 65 deg. fahr. Air is drawn through the air washers, located in the basement, and is discharged into the basement by blowers. This washed and cooled air passes through louvered openings into the machine foundations and is taken up by the machines, circulated through them, and discharged into the generator room. From here it is drawn down again into the washers, mixing with the desired amount of cool air from the outside to maintain the correct temperature, and the cycle is repeated. The inside of the building is under a static pressure of about ⅛ in. in the generator room and ⅝ in. in the basement so that any leakage is out of the building rather than into it, which eliminates the possibility of any acid gas fumes around the machines and switchboards to injure insulation or tarnish metal fittings.

The temperature of the air flowing into the air washers is automatically maintained by means of thermostatically controlled louvers, a double set being used, one set opening into the building from the air washer intakes, and the other set opening to the outside of the building. These are mechanically interlocked so that as one opens, the other closes. When cool air is being drawn from the outside, a similar amount of heated air will be discharged through louvers at the top of the building.

The air for machine ventilation is circulated by two Buffalo Forge No. 14, single inlet, duplex conoidal fans. These are three-quarter housing type, top discharge with a capacity of 71,430 cu. ft. per min. at 192 rev. per min. against ½ in. static head. Each fan is driven by a 25-hp., 440-volt, three-phase induction motor. The cooling air is washed by two Buffalo Forge carrier generator coolers each having a capacity 72,000 cu. ft. per min. Thirty gallons of fresh water per minute is continuously replacing the water in each air washer sump to prevent building up the sulphuric acid content.

The generator building will be heated in winter by air discharged from the machines. There is a possibility that there will be enough surplus heated air to assist in heating the cell room located adjacent to the generator building.

ELECTROLYTIC CELLS

Cell Construction. Each electrolytic cell contains 10 aluminum cathodes and 20 lead anodes. The 10 aluminum cathodes are approximately 1 ft. 8¾ in. by 3 ft. 4¾ in. by ⁵⁄₃₂ in. thick, and are suspended in the electrolyte contained in a lead-lined wooden box. Each cathode has two lead alloy anodes, one arranged on each side, and each one spaced ½ in. from the cathode.

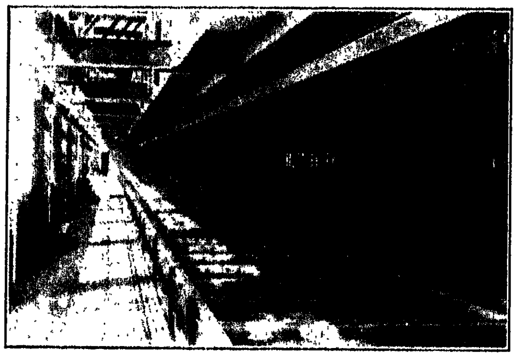

FIG. 8—ELECTROLYTIC CELLS

The anodes which are slightly smaller than the cathodes are approximately ¼ in. thick. Each cell group consists of 150 cells with the electrical circuit connected in series. The present installation consists of two such cell groups. Fig. 8 shows the cells before the anodes and cathodes were installed.

Anodes and Cathodes. The lead alloy anodes are made in the form of flat grids, being perforated with square holes. The aluminum cathodes are smooth, flat sheets.

Two anodes are used with each cathode to:

1. Facilitate the flow of electrolyte between the anodes and cathodes.

During electrolysis the circulating electrolyte enters the space between the anode and cathode through the holes in the anode. By using two anodes for each cathode it is possible to have a space between the two anodes of the two adjacent cathodes from which is taken the supply of electrolyte that is circulated between the anode and cathode. Thus, the zinc content of the solution at all places between the anode and cathode is nearly uniform.

2. Reduce the current density in the anodes and so reduce electrical losses resulting in higher cell efficiency.

3. Reduce gassing at each anode. More gassing takes place at the anodes than at the cathodes. Excessive gasing at the anodes will result in gas pockets which reduce the amount of surface of the anodes which are exposed to the electrolyte and so lower the cell efficiency.

Electrolyte. Purified zinc sulphate solution is fed to the cells and recirculated until approximately 90 per cent of the zinc has been extracted from it. The purified solution going to the cells contains over 20 per cent zinc. The liquor returned to the agitator tanks after the zinc is removed contains approximately 28 per cent acid. The cell solution is circulated continuously and at intervals a portion is removed to the acid storage tanks.

There is parallel flow of electrolyte to the cells: that is, each individual cell of the series is fed from a common supply and the effluent electrolyte from the cells is collected in a common sump from which it is pumped back to the supply tank, thus completing the circuit of flow. The electrolysis is continuous so that the electrolyte is gradually depleted of its zinc content and increased in acidity. The process, in respect to the electrolyte, is cyclic in its operation but continuous in respect to the electrolysis.

The decomposition voltage of zinc sulphate is 2.36 volts, but the minimum allowable voltage per cell is 3.1 volts in order that zinc may be positively deposited on the cathodes. Each cell acts, naturally, as a storage battery, so that if short circuited, there is a counter e. m. f. of 2.7 volts per cell. There is, of course, a very heavy instantaneous current flow which falls rapidly to zero.

The potential drop per cell depends upon several factors such as conductivity of the electrolyte and the spacing and composition of the electrodes. Due to the fact that several of these variables may be subject to change in practise or upon further developments of the process, there is a possible range of 3.4 volts to 3.7 volts per cell with an average of 3.55 volts. These conditions may be met by varying the number of cells in series, and provisions have been made for this in selecting 150 as the number of cells per circuit.

Current Density. The 150 cells of any one unit are connected electrically in series. The ten cathodes in each cell are connected in parallel and divide the 8000-ampere current flow equally among them. Hence, there are 800 amperes flowing in each cathode, and the current flow at each surface of the cathode is 400 amperes. The current density at each surface of the aluminum cathodes is therefore slightly less than 100 amperes per sq. ft.

Current density in the cells is limited by two factors:

1. It may be as high as the cell will permit without excessive circulating and recurrent cooling of the solution before returning it to the agitator tanks.

2. It is limited by the necessity of keeping down power consumption.

Cell Efficiency. Calculations on zinc tonnage and other factors are based upon 85 per cent current efficiency. Under normal operating conditions the efficiency is considerably in excess of this, but at times it may fall to 80 per cent due to impure solutions.

Stripping Zinc Deposit. The electrolytic zinc deposited on the aluminum cathodes can be stripped at varying intervals of 12, 18, or 24 hr. The stripping is done without interrupting the circuit. A cathode is disconnected from its clips by being raised and suspended above the cell for drainage of acid electrolyte. The zinc is then stripped from the aluminum cathode and the latter is replaced in its copper clips. A group of five or ten cells in a unit of 150 cells can be short circuited at one time by a copper bar carried on an overhead track. After the short circuiting bar is in place across the header bars these cells may be cleaned and repaired before being again placed in service.

TELEPHONE, RELAYS, AND ALARMS

Telephones. The generating room has a telephone connected with the Washington Water Power Company's transmission telephone system, so that in case of failure of power the attendant at the plant may communicate with the power company's system operator at once. There are also local telephone connections with the operators' residences, the office, and various parts of the plant, as well as with the city telephone system.

Relay Protection. The "running" oil circuit breakers for the synchronous motors and the 2300-volt plant feeder oil circuit breakers are tripped by both undervoltage and overload. The 6000-ampere d-c. air circuit breakers in the cell circuits trip from both overload and reverse current. The 110-kv. oil circuit breaker protecting the transformer bank trips from both overload and differential relays. The tripping of any oil circuit breaker due to overload, or of any air circuit breaker due to overload or reverse current, rings the alarm bell to attract the operator's attention. Signal lights mounted with the control switches on the control switchboard indicate which switch has operated.

Alarms. The Washington Water Power Company's substation normally receives power from two transmission lines, one 110-kv. and one 60-kv. line. The 110-kv. line is connected through an oil circuit breaker to the 110-kv. bus and the 60-kv. line through a transformer bank and oil circuit breaker to the 110-kv. bus. An auxiliary switch on each of these oil circuit breakers is connected by means of an overhead line to a signal in the Sullivan Mining Company's generator building so that upon power failure the operator will know if one of these oil circuit breakers opened.

COTTRELL PRECIPITATOR

General Arrangement. The gases from the roasting furnaces pass through a balloon type flue running up the hillside to the Cottrell precipitator located at the base of the stack. After passing through the precipitator these gases pass up the stack and out into the air currents.

The Cottrell precipitator is of the plate type consisting of ten sections divided into two groups of five sections each. Two high-voltage d-c. busses run the length of the Cottrell Precipitator Building. A suitable switching arrangement makes it possible to connect any section to either bus. The first four sections will normally operate at a higher voltage to give higher precipitation efficiency.

Equipment. The high-voltage direct current is supplied from two synchronous motor driven disk type rectifiers. Each rectifier disk gets high voltage alternating current from a 15 kv-a. single-phase transformer which has a 400-volt primary with reduced voltage taps and a 60,000-volt secondary. A variable grid resistor in series with the primary of the transformer makes it possible to adjust the voltage between taps.

Dust Recovered. The gases that pass through the Cottrell precipitator contain daily about 13.5 tons of dust or about 10 per cent of the concentrate fed to the furnaces. This dust consists mainly of zinc, lead, and silver compounds. The Cottrell precipitator removes most of this dust from the gases.

INDIVIDUAL MOTOR DRIVES

Mechanical power throughout the plant is furnished by 440-volt, three-phase motors. One means of attaining flexibility of plant operation was to install individual motor drives wherever practicable.

There are 156, 440-volt, three-phase motors connected to apparatus in the plant, the size of which range from ½ hp. to 150 hp.

Safety fused cabinets located at convenient places in the plant provide distribution points for power to the motors. To make them safe for the men to operate, all small motors are controlled by push button stations which operate magnetic contactors that are protected by fused safety switches. The larger motors are controlled by hand starting compensators which are protected by fused safety switches.

CONCLUSION

Throughout the design of the plant every effort was made to select and install equipment to facilitate flexibility of plant operation. This is particularly desirable in a plant of this type so that refinements in the metallurgical processes can be added without radical changes to the initial installation.

The writer wishes to acknowledge the helpful suggestions of Messrs. A. C. Stevenson, James B. Fisken, and L. R. Gamble, and the assistance of Mr. W. G. Woolf in the preparation of this paper.

Great Northern Railway Electrification
in the Cascades

BY EDWARD L. MORELAND[1] and RALPH D. BOOTH[1]
Fellow, A. I. E. E. Associate, A. I. E. E.

Synopsis.*—The paper gives first a brief history of the series of improvements to better operating conditions over the Cascade Range which have been undertaken by the Great Northern Railway since the line was put in operation in 1893, and refers briefly to the three-phase electrification of the Cascade Tunnel put in operation in 1909.*

The paper next gives (Part II) a description and the principal operating characteristics of the motor-generator type of locomotives now in service on the electrified section from Skykomish (Washington) to Cascade Tunnel Station, and to be used through the new tunnel and extension of electrification to Wenatchee when work now in progress is completed.

Part III gives a description of the electric transmission and distribution system along the railroad line with particular emphasis on the relay protection designed to guard the system so far as practicable against interruption of power supply at the locomotives.

Part IV describes the three-point power supply and includes a description of the frequency converter stations at Skykomish and Wenatchee for converting the 110,000-volt, 60-cycle, three-phase power purchased at these points to 25-cycle, single-phase power required for the traction service.

* * * * *

PART I.—INTRODUCTION

THE changes now in process on the Cascade Division of the Great Northern Railway in the State of Washington are the latest steps in a series of successive important changes which have been made since this part of the railroad was put in full operation in 1893, all of which have looked toward improvement of operating conditions on the difficult mountain section over the Cascade range. The present changes include the construction of the new tunnel from Scenic to Berne (7.79 mi. long, the longest railroad tunnel in America), improvement of curves at many points between Berne and Winton, the construction of the Chumstick cut-off from Winton to Peshastin, and completion of electrification from Skykomish to Wenatchee.

The first operation of the railroad across the Cascades was by means of a switch-back which worked its way over "the hill" through Stevens Pass. The grades on the switch-back were so heavy that only a few freight cars could be handled at a time, and snow conditions in the Pass during the winter rendered operation of the railroad extremely difficult.

The first major improvement in these conditions was the construction of the present Cascade tunnel completed in 1901 from Tye Station at the west to Cascade Tunnel Station at the east, a distance of 2.63 mi. This Cascade tunnel (which is still in use but will be abandoned when the new tunnel is put in operation) eliminated the switch-back operations, greatly improved grade conditions, and avoided the section of deepest snows in Stevens Pass. It still left the long winding climb up the mountain with heavy grades and sharp curves and several miles of line where it has been necessary to protect the railroad from slides of snow and rock by construction of heavy snow sheds.

The next major improvement in this section was the electrification of this tunnel in 1909, which was undertaken to eliminate the serious smoke and gas conditions which had developed with increased traffic, and to improve operating conditions for heavy freight trains though the tunnel. This electrification was planned and supervised by Dr. Cary T. Hutchinson, as consulting engineer, and was a three-phase, 6600-volt system with two trolley wires, the rails being used as the third conductor. The locomotives were equipped with three-phase induction motors and could be operated at two speeds, *i. e.*, at approximately 15 mi. per hr. on passenger trains and light freight trains and (by Cascade connection of the motors) at approximately 7½ mi. per hr. with heavy freight trains. The steam locomotives were not removed from the trains but were pulled through the tunnel along with the trains. The greater part of the smoke was eliminated as the steam engines did not work in the tunnel. Electric power for operation of the system was supplied from a small hydroelectric generating station built and operated by the Great Northern Railway at Tumwater, in Tumwater Canyon on the Wenatchee River, about 30 mi. from the tunnel but on the line of the railroad. Transmission was at 33,000 volts, three-phase, over a double circuit line on wood poles, with a step-down substation at Cascade Tunnel Station, delivering 6600 volts, three-phase, to the trolleys. This is the only example we have had in this country of three-phase railroad electrification. It was in operation nearly eighteen years, and fulfilled the limited requirements for which it was intended.

The freight service east bound carries tonnage materially heavier than the west bound. With the former steam operation, except for the electric service in the old Cascade tunnel, heavy oil-burning Mikado steam

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[1] Jackson & Moreland, Consulting Engineers, Boston, Mass.

Presented at the Pacific Coast Convention of the A. I. E. E., Spokane, Wash., Aug. 28-31, 1928.

locomotives brought the east-bound freight trains from the Interbay terminal yard near Seattle to Skykomish, the trains being made up to about 2500 tons trailing load. Skykomish is near the foot of the heavier grades on the western slope of the Cascade mountains. At Skykomish two additional locomotives (heavy Mallet type) were cut into the train as swing and pusher engines for the pull up the grades to Tye at the western portal of the tunnel. At Tye the steam helpers were replaced by the three-phase electric engines for the pull through the tunnel. This operation from Skykomish to Cascade Tunnel Station at the east end of the tunnel required a normal running time slightly in excess of 5 hr. for the 25 mi. of route, including the time of taking water at Scenic and the delay for cutting locomotives in and out of the train.

In 1925 the officials of the Great Northern Railway decided to take advantage of additional power available from the Tumwater power plant to improve operating conditions by electrifying the heavy grade section on the west slope of the Cascades from Skykomish to Tye, and utilizing electric helpers on this section. This is the ruling grade against east-bound main traffic on the entire system. On account of the complication of a double trolley and the operating limitation imposed by constant-speed operation inherent with the three-phase system, that system was not adapted for extension, and a single-phase, 11,000-volt trolley system with locomotives of the a-c.—d-c. motor-generator type was selected by the railroad officials as suitable to utilize the available facilities and to give the required service which included operation of both heavy freight and passenger trains. This scheme employs d-c. traction motors supplied with d-c. power by means of a motor-generator set carried on the locomotive. This system went into operation in February, 1927, over the 25 mi. from Skykomish to Cascade Tunnel Station, the old three-phase electrification through the tunnel between Tye and Cascade Tunnel Station being then abandoned.

For the service from Skykomish to Cascade Tunnel Station four electric locomotives were provided, descriptions of which are given later. The method of operation, on east-bound traffic, is to pull the trains into Skykomish by steam power, and there, at the foot of the heavy grade section, couple on one or more electric locomotives to pull the trains up the grade and through the tunnel. On account of the relatively short length of the present electrified zone, the steam locomotives are not taken off the trains but are run on through, assisting in pulling up the grade to Tye, but shutting off while passing through the tunnel from Tye to Cascade Tunnel Station. This method of operation has cut approximately three and one-quarter hours off the normal running time of freight trains between Skykomish and Cascade Tunnel Station.

The electric locomotives are also used to take trains down the grade west-bound from Cascade Tunnel Station to Skykomish, utilizing regenerative braking.

Comparatively soon after this improvement was conceived it was decided to improve operating conditions still further by construction of a new tunnel, now nearing completion. This tunnel lowers the summit 500 ft., shortens the route approximately 7¾ mi., eliminates over 1900 degrees of curvature, cuts down the length of the heavy grade approach, and avoids substantially all of the dangerous snow-slide area, thus eliminating 6 mi. of snow sheds. As part of this improvement it was decided (besides carrying the electrification through the new tunnel) to extend the electrification eastward from the portal of the new tunnel at Berne to Wenatchee, the eastern end of the Cascade Division, and to make extensive improvements in line and grade between Berne and Peshastin, including construction of the Chumstick cut-off which will replace the present line through Tumwater Canyon with its heavy grades and sharp curves. Fig. 1 shows an outline map of the old and the new line, and Fig. 2 shows a profile of the new line.

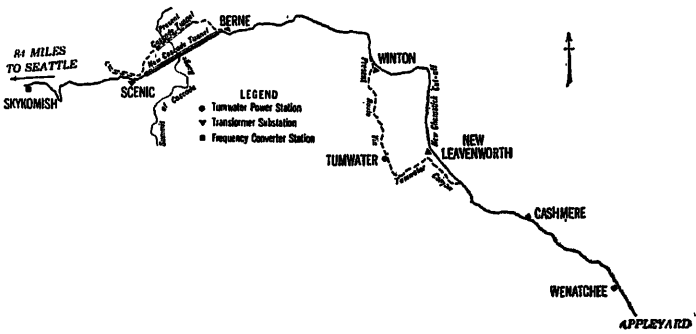

Fig. 1—Map of Electrified System of Great Northern Railway in the Cascade Mountains

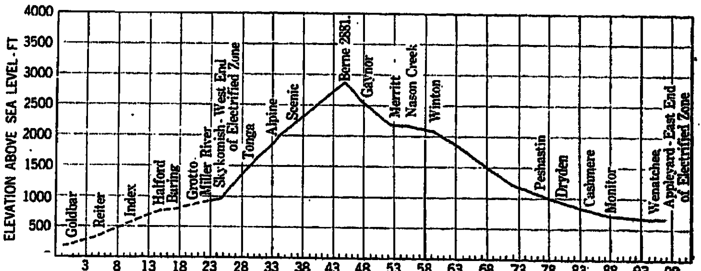

Fig. 2—Profile of Great Northern Railway in the Cascade Mountains after Completion of Present Line Changes

When these changes are completed the electrification will extend from Skykomish, Wash., at the foot of the heavy grade section west of the Cascades (84 mi. by rail from Seattle), to Wenatchee, Wash., a total distance, via the new tunnel, of approximately 72 mi., and all through trains will be operated with electric traction between these points. Five additional locomotive units are now on order for this service.

The remainder of this paper deals with the characteristics of the locomotives, the electric distribution system, and sources of electric power supply.

Part II.—Electric Motive Power

The motive power for the electrification from Skykomish to Wenatchee will consist entirely of motor-generator locomotives. The railway company now has in use two double-cab locomotives and two single-cab locomotives, and they have on order three more of the double-cab locomotives and two more single-cab locomotives. Each of the locomotives has geared, axle-slung, d-c. traction motors and has motor-generator apparatus which is mounted in the cab on a cab underframe. The single-phase power for the motors of the motor-generator sets is obtained by pantograph from the contact wire at 11,000 volts, 25 cycles per sec. It is transformed to 1240 volts on the double-cab locomotives and to 2300 volts on the single-cab locomotives. Single-phase synchronous motors operating at these respective voltages drive d-c. generators, which supply the d-c. energy to the traction motors.

The motor-generator set in each cab of the double-cab locomotives comprises a four-unit set. The four several units of this motor-generator set consist of:

1. A single-phase synchronous motor operating at 1240 volts, the armature being equipped with an auxiliary phase winding in order to provide three-phase power for starting induction blower motors. One terminal of this auxiliary phase winding is connected to an intermediate point of the secondary winding of the main cab transformer. The other terminal of this winding, together with two terminals from the secondary winding of the transformer form a three-phase system for the power supplied to the blower motors.

2. A 600-volt d-c. generator supplying power to four 600-volt d-c. traction motors permanently connected in parallel, this generator being separately excited.

3. A d-c. exciter for supplying excitation for the main synchronous motor, for the main generator, and for a separate regenerative exciter, and for charging a 125-volt storage battery which supplies the direct current for the control circuits, for starting the main motor generator set, and for driving the air compressors.

4. A 10-volt regenerative exciter, which is used for separately exciting the traction motors during regenerative braking, and also for the low excitation used for high speed motoring.

These four units are mounted on the same shaft. The motor and generator of this motor-generator set are ventilated by a fan which is mounted on the shaft between the motor and generator armatures, the air being sucked in through the two electrical machines and discharged through the fan into air ducts which lead into openings in the floor and roof. This motor-generator set is started by means of the main d-c. generator operated substantially as a series d-c. motor supplied with power from the 125-volt storage battery. When brought up to approximately one-third speed the synchronous motor is thrown on the line at reduced voltage as an induction motor, by which means it is accelerated to approximately 80 per cent of full speed before the excitation is applied. Normal voltage is applied after the motor is in synchronism. Air blast transformers are provided in each of the cabs to transform the current collected by the pantograph to the voltage required by the synchronous motor, and a blower driven by a three-phase induction motor supplies air for ventilating the transformer, this machine being provided with the necessary current as heretofore described for the blower motors. The speed of the locomotive is chiefly controlled by varying the voltage of the main d-c. generator by adjustment of its field current by adjustable resistance controlled through contactors. Higher speeds may be obtained by putting the traction motors on to separate excitation, under which conditions the field strength can be reduced approximately 50 per cent.

The motor-generator set on each of the single-cab locomotives comprises five units: 1, A synchronous motor having full three-phase armature windings but operated as a single-phase motor for driving the motor-generator set, the armature at the same time acting as a phase balancer to provide three-phase power for driving induction motors on the blowers for the traction motors. 2 and 3, Two 750-volt d-c. generators connected in series and supplying current to the three groups of traction motors. 4, A 65-volt d-c. exciter for providing current to excite the synchronous motor, the two main generators, and the regenerative exciter, and to provide control current and storage battery charging current. 5, A d-c. generator used for separately exciting the traction motors for regenerative braking and also used as a single-phase series a-c. motor for starting the motor-generator set, in the latter function being connected to a special winding on the main locomotive transformer. The complete set is made up of synchronous motor and main exciter on one shaft, the two main d-c. generators with a blower between them and the exciter for regenerative braking on another shaft, the two being coupled end to end through a flexible coupling. The main locomotive transformer is arranged for air blast, two blowers being provided, each being driven by a single-phase repulsion commutator type motor to supply the ventilating air.

The speed of the locomotive is chiefly controlled by varying the voltage of the d-c. generators by adjusting the field current by adjustable resistance controlled through contactors, but the traction motors are equipped with field shunting means, with two operating positions, which permit operation down to 50 per cent of field strength.

Each cab of the double-cab locomotives is equipped with four 600-volt d-c. traction motors, axle-slung, permanently connected in parallel. Each motor has a one-hour rating of 540 hp. with forced ventilation, and drives one driving axle of the locomotive through a flexible or cushion type gear mounted on the hub of each driving wheel. These locomotives were the first type purchased for operation on the electrification from Skykomish to Tye and thence through the old Cascade Tunnel to Cascade Tunnel Station, and were designed primarily for operation as common motive power equipment for both passenger and freight service. As now operated each of these locomotives consists of two cabs operated as a unit, and is of the $1 - D - 1 + 1 - D - 1$ type.

Each single-cab locomotive is equipped with six 750-volt motors, axle-slung, each driving one driving axle and geared to its axle through cushion-type twin gears. These motors are permanently connected with two in series and the pairs in parallel. Each motor has a one-hour rating of 550 hp. when ventilated with 3500 cu. ft. of air per minute.

These locomotives were purchased after the decision to build the new tunnel and to extend the electrification eastward, and are designed for higher maximum operating speeds as the specification placed more emphasis on their use as passenger locomotives. Each of these locomotives is of the articulated $1 - C + C - 1$ type.

A summary tabulation of the mechanical and electrical characteristics of these two types of locomotives is presented in Table 1.

TABLE I
LOCOMOTIVE CHARACTERISTICS

	General Electric Co. Single Cab Locomotive	Westinghouse Elec. & Mfg. Co. Double Cab Locomotives
Number of locomotives	4	5
Mechanical		
Classification	1–C+C–1	1–D–1+1–D–1
Total weight each locomotive	518,000 lb.	715,000 lb.
Weight on drivers	409,800 lb.	549,600 lb.
Weight per driving axle	68,300 lb.	68,700 lb.
Maximum rigid wheel base	15 ft. 4 in.	16 ft. 9 in.
Total wheel base	58 ft. 8 in.	78 ft. 11 in.
Height over pantograph locked down	15 ft. 3 in.	15 ft. 10 in.
Electrical		
Number of motors	6	8
Horsepower 1 hr. rating	550 per motor 3300 per locomotive	541 per motor 4330 per locomotive
Tractive effort 1 hr. rating	67,200 lb.	112,500 lb.
Speed full field 1 hr. rating	18.2 mi. per hr.	14.4 mi. per hr.
Horsepower cont. rating	3,000	3,600
Tractive effort cont. rating	60,500 lb.	88,500 lb.
Speed full field cont. rating	18.6 mi. per hr.	15.5 mi. per hr.
Voltage synchronous motor	2,300	1,240
Voltage d-c. generators	750 each, two in series	600
Voltage on traction motors	1500 volts on two motors permanently in series	600 volts all motors in parallel
Capacity of motor-generator set continuous	1-2500 kw.	2-1500 kw. each

Locomotive inspection and maintenance for the four electric locomotives now in service between Skykomish and Cascade Tunnel Station are at present handled at the steam locomotive repair shops at Skykomish. A new electric locomotive shop with complete facilities for this work is now under construction at Appleyard (Wenatchee) and will be available for service upon completion of the present extension. All work on the electric locomotives will be handled in the new shop.

PART III.—ELECTRIC DISTRIBUTION SYSTEM

Contact System. The initial installation of this Great Northern electrification covers some 25 route miles and consists of 25 mi. of main line electrification plus approximately 6 mi. of electrified sidings and yards. This installation runs from Skykomish to the old Cascade Tunnel yard. The extension now being put into service connects with the old line at Scenic and extends over the new route as shown in the map, Fig. 1, to Appleyard, which is a large freight yard just east of Wenatchee. These sections of the railroad consist entirely of single main track construction. Yards at Appleyard and at Skykomish and passing tracks at Scenic, Berne, Winton, Cashmere, and Wenatchee are included in the electrification.

The catenary system over all tracks provides the required current carrying capacity without the use of additional feeders except across the Tongo loop in the existing construction between Skykomish and Scenic. At this point light construction is used around the loop and a heavy feeder ties across the two ends of the loop, the feeder being carried on poles used for the transmission line which also cuts across the loop. The design of the distribution system provides for a maximum regulation of approximately 10 per cent under normal traffic conditions with a trolley feeder section open at a substation. This regulation was found to be desirable on account of the characteristics of the synchronous motors employed for driving the motor-generator sets on the locomotives.

Wood pole and bracket construction is used in general for all single track construction, except on some curves where cross-span construction is used, and multi-track construction is of the cross-span type except where guyed structures could not be employed, and at these points wooden poles with expanded metal trusses are used.

The catenary system employed for this electrification consists of a combination of inclined catenary on the curves and simple catenary with loop hangers on the tangents. A composite main messenger of high tensile strength and a single bronze contact wire are used in all sections except through the New Cascade Tunnel where a copper messenger and a copper contact wire are permissible because of the lower temperature ranges and consequent lower stringing tensions. Bronze contact wires on the system in general were justified, because of high strength rather than for wearing qualities, since the traffic over the line is relatively light. The hangers employed in curve construction are the solid type hanger clamped rigidly to the messenger and trolley; the hangers used in tangent construction are of the simple, light weight, loop design, and both types are completely non-ferrous. Non-ferrous cross-span wire is employed in the yards at Appleyard, where considerable steam locomotive operation will continue. Steel cross-span wire construction is used on sidings and passing tracks in those sections of the line where operations will be completely electrified, and also at the present terminal at Skykomish since at the time Skykomish yard was installed it was assumed that electrification would probably go on to Gold Bar in a relatively short time.

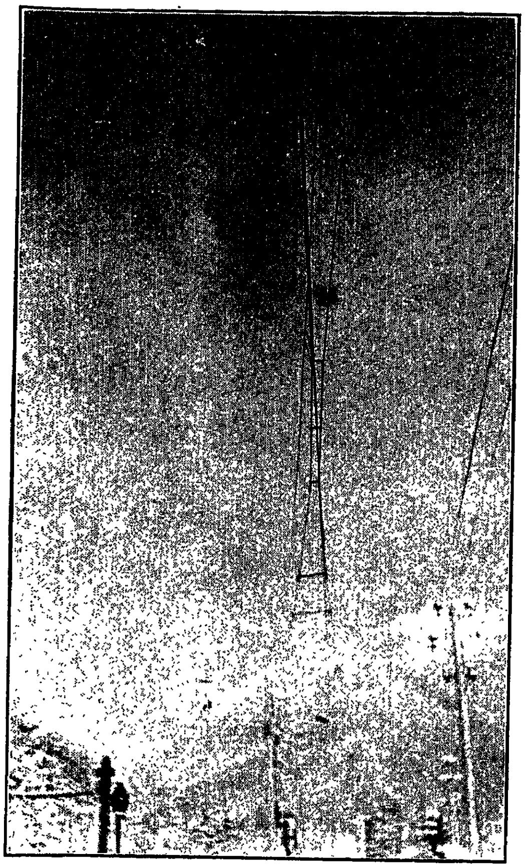

Fig. 3—Catenary Construction

The main messenger in the heavy grade sections of the main line track consists of nineteen strands of number 7 wire. The inner seven wires are of calsun bronze in the existing sections of the electrification and of red brass in the newer sections. The outer twelve wires in each case are of hard drawn copper. The trolley wire in the existing section of the main line is 4/0 "Hitenso C" bronze wire of 55 per cent conductivity and in the newer sections is 4/0 "Hitenso A" bronze wire of 80 per cent conductivity. This gives a conductivity of 390,000 cir. mils equivalent in those sections now electrified and 456,000 cir. mils in the newer sections. Siding construction consists of a 3/8 in. calsun bronze messenger and a 3/0 "Hitenso C" trolley wire.

The catenary system on the main line has a normal tension of 4000 lb. in the messenger and 2500 lb. in the 4/0 trolley wire, with a maximum tension under Class B (N. E. L. A.) loading of 7000 lb. in the messenger and 4000 lb. in the 4/0 trolley wire.

The tangent track construction, as noted before, is of the side bracket type, employing two 1½ by 2½ by ¼ in. galvanized steel angle bars placed back to back as a mast arm and a 5/8 in. hog rod. Pin insulators of 45,000 volts normal voltage are used for the messenger with this type of construction on all tangent tracks. Three suspension insulator disks in series are used on curves and on multiple track construction and in the new long tunnel, although four disks in certain particularly severe locations in the old construction were found necessary.

The line design in general is based upon a normal spacing of poles on tangent track of 150 ft. This spacing could not be adhered to rigorously, since the line consists of many curves with short lengths of tangent track between, and in order to obtain equipoise span construction it was necessary to shorten the spacing to adapt it to the requisite number of spans of uniform or equipoise length. Hanger spacings of 15 ft. were employed, the shortest hanger being located 7½ ft. from the low point of the span, accommodating the resultant spacing at the point of support in order to use standard hanger lengths rather than to have a number of special hangers. On curve construction, as previously noted, inclined catenary was used, made up with solid hangers. In order to obtain a line without cusps in the contact wire, and to preserve a high factor of safety in pantograph clearances by maintaining an angle between the hanger rods and horizontal of 22 deg. or better, it was determined that 4 deg. was the maximum curve on which inclined catenary should be used without pull-offs, and that all curves of shorter radius should be made by utilizing an inclined catenary system of 4 deg. curvature pulled over by means of pull-offs. A maximum deviation of 9 in., from the center line of the track, and a maximum middle ordinate

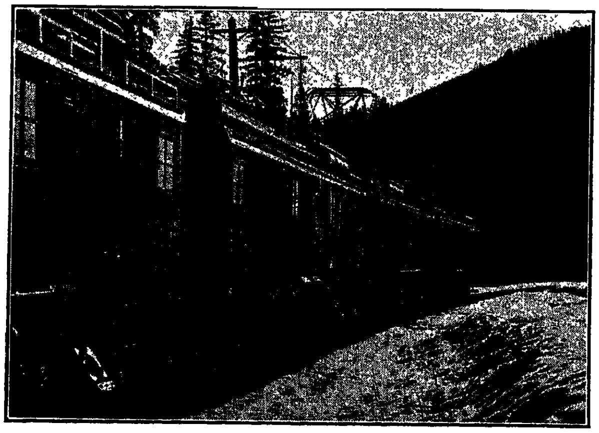

Fig. 4—Catenary Construction at Tongo Loop

distance of 15 in. were determined upon for normal temperatures. With these limitations it was found that 150-foot span lengths could be maintained on tangents and on all curves up to and including 6 deg. Curves of 7 deg. and 8 deg. were designed up to a maximum span length of 120 ft.; 9 deg. curves up to 105 ft.; and 10 deg. curves up to 90 ft.

Jumpers between the main line messenger and contact wires are inserted every 500 ft. in the tangent sections (where loop hangers are employed), but no jumpers are used on curves, since the hanger design provides for a solid connection from the messenger to the contact wire at these points.

Contact line construction in general consists of messenger sections of approximately 10,000 ft. in length in all sections of the line except through the long tunnel. The messenger is dead-ended at each end of these sections and is by the type of construction, insulated from the adjacent messenger sections. Jumpers are employed between the messengers of the various sections except at transformer substations where the two sections of messenger are tied together through the 11,500-volt bus in the substations. The yard construction at Skykomish and Appleyard is so designed that the yard is fed separately from the transformer substation at each of these locations.

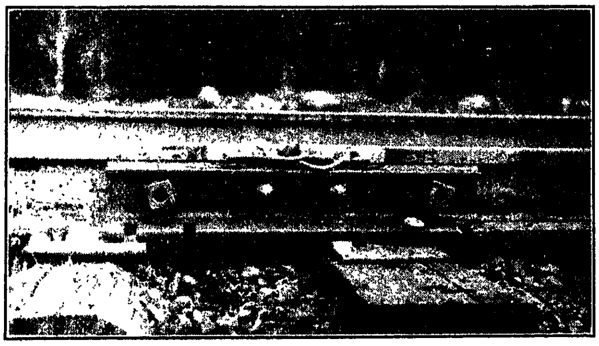

FIG. 5—TYPICAL RAIL BOND INSTALLATION

Bonding. Gasweld bonds have been used throughout the entire electrification. The initial installation employs one 2/0 double strand U type Gasweld bond per rail joint. The new installation, at present under construction, will employ two No. 2 Gasweld single strand bonds per rail joint. All special work is bonded with 4/0 bonds. Impedance bonds are installed adjacent to each substation location. No negative return wires are used except at the Tonga loop cut-off, previously referred to.

Relay Protection. Of the arrangements for relay protection for the electrification circuits, perhaps the most interesting feature is the arrangement adapted for protection of the transformer substations. The protection which is required is against faults in the substation itself, faults on the 11,500-volt contact wire system, and faults on the 44,000-volt transmission system respectively.

For the clearing of faults occurring in a transformer substation differential current protection is used, the relays being energized by bushing type current transformers in the incoming 44,000-volt transmission line oil circuit breakers and in the outgoing 11,500-volt trolley feeder circuit breakers. In the event of a fault in the substation these relays actuate the circuit breakers and serve to trip out both the incoming and outgoing circuit breakers, and thereby isolate the substation. This meets in a simple and economical way the necessity for protecting the outside system from the influence of a fault arising within a transformer substation, and at the same time isolates the substation so that the fault will not be propagated within the substation itself.

Protection for faults on the contact wire system and its feeders is provided by one directional impedance type relay in each such feeder. The reason for using an impedance type relay for this service arises from the relatively high reactance of the contact system, which is sufficient to limit the minimum fault current to a value that is too close to the maximum load current safely to insure discriminatory action with an ordinary directional over-current relay with a constant restraining torque. In the impedance relay the restraining torque decreases with the additional drop of substation voltage, which is caused by the relatively low power factor of the fault current compared with the operating load currents. The result is that the margin available for discrimination between a fault current and a load current when this relay is used is considerably increased by the change in restraining torque due to change in voltage.

It is also possible to have a fault of sufficiently high resistance on the contact system so that it will not cause sufficient current flow at the transformer substation to actuate the overload relays although the current is in excess of the continuous rating of the transformers. It would therefore be possible for such a fault to hold on and eventually overheat the transformer. To guard against this possibility it is only necessary to arrange that the contact making thermometers with which the transformers are equipped, located inside the transformer cases, in addition to ringing an alarm bell, will also close the trip circuit and cut the substation out of service, opening both the 44,000-volt and the 11,500-volt breakers, if the temperature of the transformer exceeds a predetermined safe limit.

By these two arrangements we secure adequate protection for faults on the contact system with a minimum of cost.

The protection for the 44,000-volt incoming lines at the transformer substations imposes rather exacting requirements upon the relay arrangement. Each 44,000-volt line is tapped, through a circuit breaker, into a common bus at each of the transformer substations. Consequently, a fault consisting of a ground or of a wire to wire short-circuit occurring on one of these circuits between any two substations should require the circuit breakers at the transformer substations to operate successively in the order of the progression of the substations away from the fault. For example, a fault on Circuit Number 1 between Winton and Tumwater requires the successive operation of circuit breakers at Winton, Berne, Scenic, and Skykomish, in the order given, before the fault is cleared from the system. The relative positions of these transformer substations along the line are shown in the diagram of the transmission and distribution system, Fig. 6. The relays at Berne should not begin their controlled cycle of operation until the circuit breaker on the faulty line at Winton has opened, since prior to this time there is nothing at Berne to indicate to the relay devices which of the two 44,000-volt circuits is in fault. The same is true successively at Scenic with respect to Berne and at Skykomish with respect to Scenic. These successive operations make it necessary to have the operating cycle of these relays at each transformer substation as short as possible so that a faulty transmission circuit may be cleared from the system promptly. The conditions also require that either of the two transmission circuits shall be free to be opened by sectionalizing switches between any of the transformer substations without interfering with the operation of the protective relays. In order to provide protective arrangements to insure rapid isolation of a faulty section of transmission line, which are not affected by unbalance between the load currents carried by the two transmission circuits, two relays are used in each transformer substation to take care respectively of short circuits and ground faults, one (marked relay *P* in Fig. 7) being a directional over-current relay actuated by heavy unbalance between the line currents in the two incoming transmission lines and the other (marked relay *Q*) being a directional over-current relay actuated by slight unbalance between currents in the two transmission lines associated with flow of current in the neutral ground connection of a substation transformer. Fig. 7 shows diagrammatically the connection utilized for these two relays. In order to minimize the investment required in the protective system, it is desirable to energize the relays from bushing type current transformers, for which there are only four available locations in the terminals of the two 44,000-volt oil circuit breakers. This is accomplished by the circuit arrangement shown in Fig. 7 already referred to. It will be observed that the current flowing in the current coil of relay *P* is proportional to the difference between the currents in the conductors *A* and *C* (*i. e.*, the unbalance between the line currents), whereas the current flowing in the current coil of relay *Q* is proportional to the difference between *A*–*B* and *C*–*D* (*i. e.*, the unbalance of residual current in the two circuits). The relay *P* is given a sufficiently high current setting so that it will not be actuated by the unbalance of load current resulting from an open circuit in one of the transmission circuits. It will, however, operate on the heavy unbalance resulting from an accidental contact or short circuit between the two conductors of one circuit. The current in the coils of relay *Q* is always equal to zero

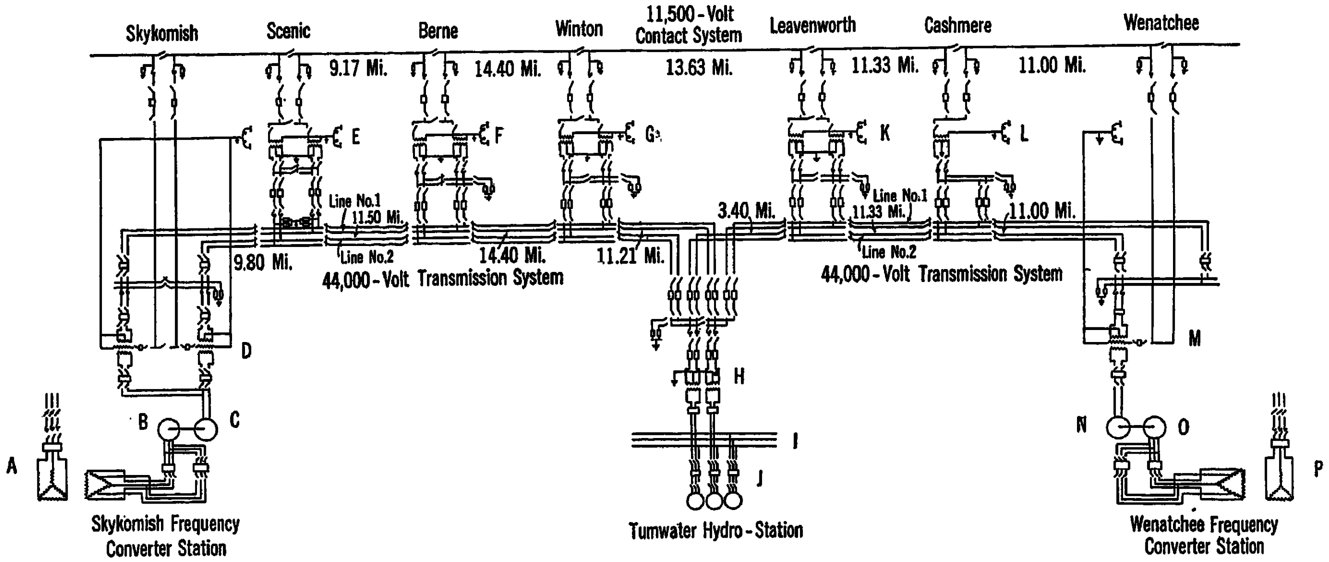

FIG. 6—GENERAL WIRING DIAGRAM OF ELECTRIFICATION CIRCUITS

A. Three 2750 kv-a. transformers, 60 ~ 110/13.2 kv.
B. Motor 13.2 kv. 60 ~, 3φ, 8250 kv-a.
C. Generator 13.2 kv., 25 ~, 1φ, 7500 kv-a.
D. Two transformers 7500/5000 kv-a., 44/13.2/11.5 kv.,
E. Two transformers 2500 kv-a. each, 44/115 kv., 25 ~
F. Two transformers 2500 kv-a. each, 44/115 kv., 25 ~
G. Two transformers 1500 kv-a. each, 44/11.5 kv., 25 ~
H. Two transformers 3750 kv-a. each, 6600/44,000 volt, 1φ, 25 ~
I. 6600-volt bus
J. Three generators 2500 kv-a. each, 6600 volt, 3φ, 25 ~
K. Two transformers 1500 kv-a. each, 44/11.5 kv., 25 ~
L. One transformer 2500 kv-a., 44/11.5 kv., 25 ~
M. One transformer 7500/5000 kv-a., 44/11.5 kv., 25 ~
N. Generator 13.2 kv., 25 ~, 1φ, 7500 kv-a.
O. Motor 13.2 kv., 60 ~, 3φ, 8250 kv-a.
P. Three transformers 2750 kv-a. each, 60 ~, 110/13.2 kv.

unless there is a ground in the transmission circuit. Therefore, this relay is unaffected by any degree of load unbalance and can be given a current setting sufficiently small so that the relay will respond in the minimum of time to the smallest ground fault which is likely to occur. As indicated in Fig. 7, the potential coil of relay *P* is energized from a potential transformer on the 11,500-volt trolley feeder bus and the corresponding coil on relay *Q* is energized from parallel current transformers in the neutral ground connections of the substation transformers, so that the directional elements of the relays will discriminate in such a way as to trip the circuit breaker of the faulty circuit.

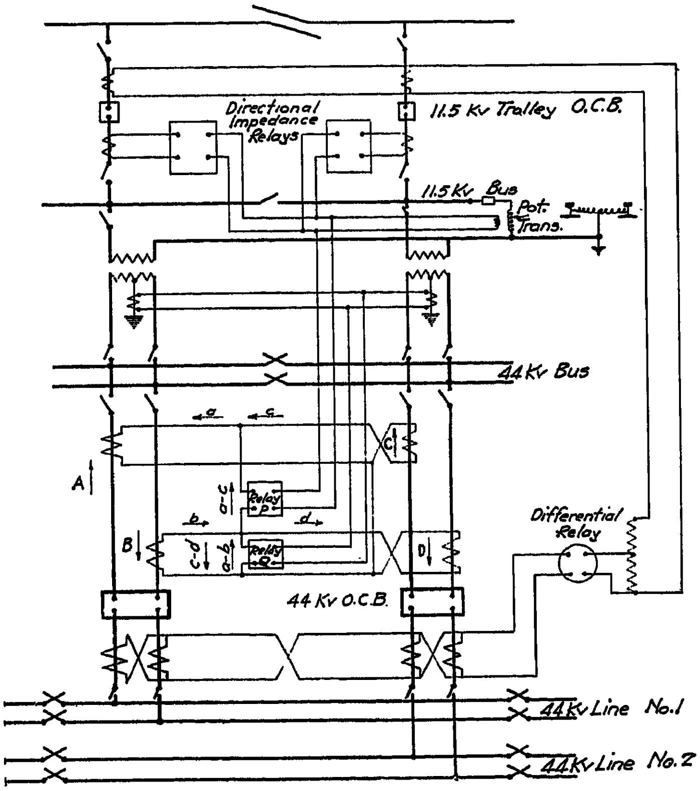

FIG. 7—TRANSFORMER SUBSTATION RELAYING—SCHEMATIC DIAGRAM WITH TRIPPING CIRCUITS OMITTED

Note: All disconnecting switches are normally closed
Current transformers in transformer neutral leads are instrument type
All other current transformers are bushing type
Contact making thermometer in each transformer is arranged to trip all our circuit breakers in case of excess transformer temperature

This combination of relays satisfies the requirements of the system, namely, to procure high sensitivity and quick action for ground faults whether of large or small magnitude, in combination with freedom from actuation occurring due to open circuits, and these results are accomplished with economical expenditure for equipment. No special auxiliary switches are required in the relay trip circuits, and the only additional instrument transformers compared with the number that would have to be used for straight directional overload relay arrangements are the current transformers placed in the neutral ground connection of each station transformer. Auxiliary locking relays are provided to prevent opening of the circuit breaker on the good line as a result of rebound of the directional element after a circuit breaker on a faulty line has opened.

The protection associated with the 44,000-volt transmission lines and the 11,500-volt contact system at the frequency converter stations and with the 44,000-volt transmission lines at the Tumwater generating station is of similar character to that at the transformer substations. For the remainder of the equipment in the circuits in the converter stations, the protective devices introduced for faults within or without the station are of the usual differential and overload character that is commonly associated with motor-generator stations and high potential transformers.

A somewhat special type of relay protection is provided at the two frequency converter stations for the 13,200-volt signal power feeder which runs between the two. This 60-cycle, single-phase, 13,200-volt circuit is connected directly to the 13,200-volt, 60-cycle, auxiliary power bus at each frequency converter station. The circuit supplies power for operation of the signal system, for lighting the new long Cascade Tunnel, and for miscellaneous purposes.

There is a number of sectionalizing switches in this signal power feeder circuit, and it is intended that one of them shall always be open, thereby providing for independent supply of power to each section from one frequency converter station. There is a possibility of this circuit being closed so as to connect through from converter station to converter station, in which case there might be an excessive flow of current over the circuit which is of No. 6 copper wire. In order to provide against the contingency of an excessive flow of current the circuit breaker controlling this circuit at each converter station is actuated by a directional over-current relay of the usual type, except that the trip circuits of the over-current element and the directional element are connected to operate independently. The operation of the over-current element causes the circuit breaker to trip on the occurrence of excess current in either direction and the operation of the directional element causes the circuit breaker to trip whenever there is any flow of power towards the bus.

PART IV.—ELECTRIC POWER SUPPLY

The power requirements for electric service in the section from Skykomish to Appleyard are materially in excess of the capacity available from the present Tumwater plant, and a sufficient independent power supply appeared to be more costly than purchased power from existing commercial hydroelectric power properties. A plan was therefore worked out by the Great Northern Railway officials with the Puget Sound Power & Light Company whereby the power company took over the operation of the Tumwater power station and contracted to sell to the railroad all of the electrical service required for operation of the railroad west of Wenatchee. To meet the requirements of the electrification now in operation between Skykomish and Cascade Tunnel Station the power company supplies 25-cycle, single-phase power to the railroad company's step-up substation at Tumwater, and also supplies 60-cycle, three-phase, 110,000-volt power to the railway company's high-tension transmission line at Gold Bar for transmission to a frequency converter station at Skykomish, the western end of the present electrification. To meet the added requirements imposed by extension of the electrification to Appleyard (Wenatchee), power will also be delivered by the power company at Wenatchee, at 60 cycles, three-phase, 110,000 volts, where it will be converted to 25-cycle, single-phase power for transmission to the transformer substations. Under the terms of the power contract the demand for billing purposes is determined from the simultaneous demands at the three points of delivery.

Fig. 6, previously referred to, shows in diagrammatic outline the circuit and substation arrangements for the completed electrification from Skykomish to Appleyard.

Purchase of power under the contract arrangement is cheaper than the cost would have been for developing an independent source of supply of sufficient capacity to meet the maximum requirements of the system, and also gives materially greater assurance of continuity of service than would have been possible from an individual power station.

The plan developed gives three points of supply, namely, at Skykomish, Tumwater, and Wenatchee, with double circuit, single-phase, 44,000-volt transmission lines connecting the three sources of supply and serving the intervening transformer substations along the railroad route. With this arrangement failure of any one source of supply or failure of both 44,000-volt transmission circuits at any one point cannot cause serious interruption of railroad service.

The two frequency converter stations, at Skykomish and Wenatchee, are supplied with 60-cycle current from transmission lines feeding from two separate points in the power company's system, the line supplying Skykomish coming from the Beverly Park substation, and the line supplying Wenatchee coming from the White River generating station, so that the probability of simultaneous failure of high-tension power supply at Skykomish and Wenatchee is minimized. An interconnection between the Puget Sound system at Wenatchee and the Washington Water Power Company's new hydroelectric plant at Lake Chelan is now under construction, which will still further add to the assurance of continuity of power supply.

Three point supply also makes possible materially better voltage regulation on the 25-cycle system of the railroad than would have been possible with single point supply, and also makes possible economies in design of the 25-cycle transmission system serving the transformer substations.

Purchase of power from a large commercial power system also has a distinct advantage over independent generation by the railroad company in that it offers an adequate power load for absorbing the power produced during regenerative braking when there are not sufficient electric power demands on the railroad system itself to absorb this power, and consequently it obviates the necessity of providing a complicated system of rheostats available for absorbing excess regenerated power.

At the Wenatchee frequency converter station power is received at 110,000 volts, three-phase, 60 cycles, and is stepped down to 13,200 volts, three-phase, passed through a 7500-kv-a. frequency converter, which converts the power to 25 cycles, single-phase, at 13,200 volts, which is stepped up to 44,000 volts for transmission to the transformer substations. Each frequency changer is equipped with a stator shifting device in order that the load may be properly distributed between the two ends of the electrification system when three point supply is put in operation, and to prevent improper load distribution due to load variations in the power company's system, which will be interconnected between Skykomish and Wenatchee both through the railroad company's 44,000-volt transmission line and the power company's high-tension transmission system.

In the original installation at Skykomish, 25-cycle, single-phase power for the contact system on the railroad was obtained by stepping down from 44,000 volts to 11,500 volts through separate transformers. These separate transformers are now being replaced by tertiary windings on the transformers that are used to step the 25-cycle voltage up from 13,200 volts to 44,000 volts.

The frequency converter station at Wenatchee, which is now under construction, has the same essential characteristics as the Skykomish frequency converter station, and will be provided with a three-winding transformer for stepping the 13,200-volt, 25-cycle power up to 44,000 volts for transmission to the transformer substations, and for supplying 11,500-volt power to the contact system at Wenatchee.

The type of construction employed at the frequency converter stations is as simple and inexpensive as is consistent with the reliability requirements. The step-down equipment on the 60-cycle side of each frequency converter station is of the conventional single bus outdoor substation type as shown in the illustration of the step-down substation at Skykomish given in Fig. 8. The 25-cycle step-up substation is of a similar type of construction except that rigid bus design has been used throughout the substation. This construction is shown in Fig. 9. The frequency converter at Skykomish is installed in a building adequate for the future installation of an additional unit, and the frequency converter station at Wenatchee is so planned that it can be readily extended to provide for installation of a second frequency converter unit in that station if it should ever be required. The indoor construction consists of 13,200-volt switch gear, with no low-tension bus work other than that necessary for obtaining auxiliary power in the substation. The layout for future construction contemplates, in the event of installing a second frequency converter at either station, that the frequency converters will not be paralleled directly on low-voltage busses at any point, that the motors will be paralleled only on the 110,000-volt, 60-cycle bus and the 25-cycle generators will be paralleled only on the 44,000-volt bus, or as necessitated on the 11,500-volt traction bus through the tertiary windings of the three-winding transformers.

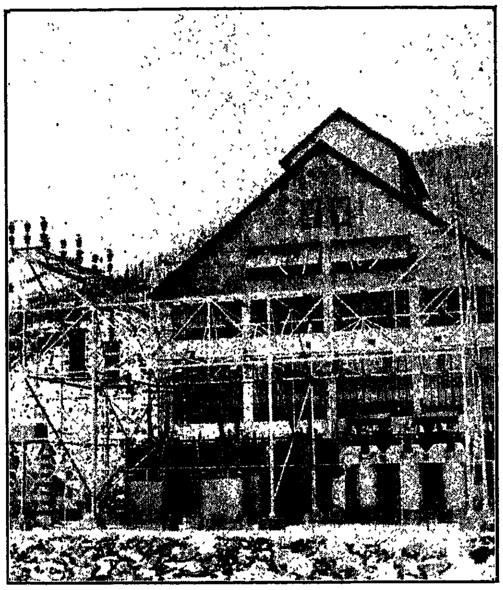

Fig. 8—Skykomish Frequency-Converter Station

60 ~, 110,000/13,200 volt substation

The use of three-winding transformers at the frequency converter stations, which serve also as transformer substations for supply of traction current to the trolley circuit, permits economies in the investment and also material savings in the operating expense of the system by eliminating a large part of the core loss which would be incurred by the installation of separate transformers for supplying the traction service.

The transmission system connecting the transformer substations along the line with the frequency converter stations and the Tumwater power station consists of a double circuit, single-phase, 4/0, 44,000-volt transmission line running from Skykomish to Tumwater and from Tumwater to Wenatchee, and tapped into the various transformer stations between these points. From Skykomish to Scenic, from Berne to Winton, and from Leavenworth to Wenatchee, these circuits are carried on the wood poles which support the contact system. The section of the transmission line from Scenic to Cascade Tunnel Station runs directly over the mountain, and is of the H frame, flat type of construction. The section from Cascade Tunnel Station to Berne is wood pole construction running adjacent to the old railway right-of-way. At Berne the line ties in with the trolley construction. The section from Winton to Leavenworth is wood pole, two circuit construction, located on the old right-of-way as far as the eastern end of the Tumwater Canyon, at which point the line leaves the right-of-way and ties across to the new section of line in the Chumstick Valley adjacent to the new Leavenworth transformer substation. The line in general is insulated with 60,000-volt insulators having a dry arc-over voltage of 170,000 volts. The line is operated with the mid-point of all 44,000-volt transformers grounded, giving a normal working potential to ground of 22,000 volts.

The transformer substations are fed from both of the transmission circuits through oil circuit breakers, and the relaying on the transmission system is so arranged that a fault to ground or from conductor to conductor on any one circuit will remove the circuit complete from Skykomish to Tumwater or Tumwater to Wenatchee, as the case may be, and will open the substation breakers connected to the faulty line, leaving the operation of the substations unimpaired by any single line fault.

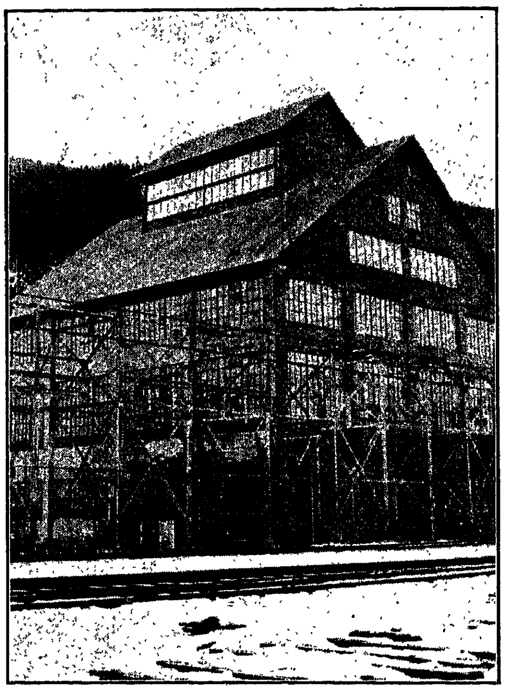

Fig. 9—Skykomish Frequency-Converter Station

25 ~, 13,200/44,000/11,500 volt substation

The transformer substations along the route are in general of the two-unit type, and consist of outdoor equipment with a high-voltage, single-phase, 44,000-volt bus, and a low-voltage, single-phase, single-conductor, 11,500-volt bus. The substation is normally operated with the 44,000-volt bus between transformers closed and normally supplied from both circuits. The transformers in each substation in normal operation are tied solidly to the 11,500-volt bus, with the sectionalizing switch in the center of the bus closed. The two transformers at each substation (where two transformers are installed) are hence normally operated as a single unit. The relaying necessary for this method of operation is described in a previous section. This method of operation as compared with operation with the 11,500-volt bus sectionalized permits a more effective utilization of the transformer capacity, since each transformer is available for service to locomotives on either side of the air section break in the contact conductor.

The location of communication circuits is such as to permit operation with the 11,500-volt bus closed. This method of operation would not be permissible with oil circuit breakers of the standard design if the trolley system of the railroad were closely paralleled by communication circuits, since fault currents resulting from short circuit would thus be permitted to extend through more than one trolley section and would produce correspondingly increased disturbance in the communication circuit.

This paper sets forth the characteristics of the electrical portions of the group of notable improvements that are being carried out by the Great Northern Railway on its Cascade Division as enumerated in the early part of the paper. The plans for the improvements and supervision of the execution have been carried out by the company's engineering department, of which Colonel F. Mears is Assistant Chief Engineer in charge of the work on the west end of the system.

The detailed plans and specifications for the electrification were prepared by the railroad company's engineering staff in cooperation with the consulting engineers, and the construction work on the extension of the electrification is, with a few minor exceptions, being carried out by the company's own forces. Mr. D. M. Burckett and Mr. J. E. Hawe are the principal assistants of Colonel Mears in direct charge of the electrification work. The construction in connection with the electrification is being carried out under their direction and supervision.

Discussion

Paul Lebenbaum: In discussing a paper such as this, it must continually be kept in mind that the men who are responsible for the operation of a steam railroad and face its many problems are not electrical engineers; they are men who have grown up with the steam locomotive, which, in the last ten years, they have so improved as to enable it almost to keep pace with the tractive power possibilities, though not the speed, of the electric locomotive. Therein lie both the strength and the weakness of the electric locomotive. A steam machine good for large tractive powers at slow speeds is at the same time so counterbalanced and has the necessary horsepower to enable it to run at speeds on the level of from 50 to 55 mi. per hour, so that the same locomotive, with helpers on a mountain grade, can take a tonnage train in level or rolling territory at speeds that the present designs of mountain-type electric locomotives cannot attain.

The Great Northern electrification is of course a compromise of what may be considered best in both the a-c. and the d-c. systems. An 11,000-volt, single-phase trolley, avoiding the necessity for heavy feeders; a synchronous motor on the locomotive, assuring unity power factor, and the use of d-c. traction motors, with an almost infinite number of speeds through exciter control of the d-c. generator, make for a comparatively simple design. Whether it is the system that will be adopted as the standard remains to be seen. I doubt it, because in an art in which changes are made as fast as in the electrical field, especially in our fundamental conceptions, I cannot feel that the present is the right time to think of standardization on any system.

M. L. Wade: Railway electrification is a subject of extreme interest to residents in the Canadian Rockies. Our problems are rather similar to both the Chicago, Milwaukee & St. Paul and the Great Northern, but for the present these are restricted pretty well to the consideration of electrifying the Rogers Pass tunnel, known as the Connaught Tunnel on the Canadian Pacific Railway. This tunnel pierces Mount Sir Donald and is approximately five miles in length from Glacier, at the west portal, to Donald, at the east end. The second unit of the contemplated electrification would probably be on the heavy grades known as the Field Hill, involving two spiral tunnels. For some years the railway company has made a study of the Columbia River near Beavermouth with this electrification in view. Our rapid mountain streams carry large quantities of debris and silt, offer very little natural pondage, and present a problem of combined engineering difficulties and high development cost—a problem which has to be attacked with much deliberation.

The salient feature of the Great Northern cascade electrification is, to my mind, the development of the 11,000-volt single-phase trolley system and the comparatively simple motor-generator equipment carried in the locomotives. It is to be hoped that the future may see this arrangement worked out satisfactorily at 60 cycles in order to get away from the cost of frequency-changer stations along 60-cycle transmission lines, tending to bring the electric locomotive into closer competition with steam on hauls of lower traffic density.

A point raised in a prior discussion was that of antipathy or lack of interest on the part of certain railway officials. To this might be added an observation on the general attitude of railroaders toward electrification. They don't like it. It is going to be a matter of long-time education to get them to like it. The general attitude of the average engineer, fireman, and trainman is this,—"The more tonnage a locomotive can handle, the fewer are the required train crews to handle a given traffic, the more lay-off's there are going to be, and the less money we can make."

C. E. Baston: The motor-generator locomotive was first put into operation, on the Detroit, Toledo & Ironton, operating over 17 miles of single track. This locomotive was designed by engineers of the Westinghouse Company, the mechanical parts being built by the railroad company and the electrical equipment being furnished by the Westinghouse Company.

The control of the Westinghouse locomotive, as you know, is by field control of the main generator. There were some problems in the development of this locomotive that required considerable thought in solution, understanding that this locomotive must be operated not by a substation operator but by an old steam engineer. Of course something had to be made that could be handled with very little introductory training. Automatic synchronizing of motors of 2000 kw. or more on a moving locomotive is quite a problem. It must be done with as few relays as possible, and those relays must not be delicate in construction.

Our aim has been to force the engine men to be in the equipment compartment watching the motor-generator set as it comes up the speed. For that reason the starting of the motor generator is not done from the operating compartment.

There are two types of motor-generator locomotives on the Great Northern, a single-cab unit built by the General Electric Company which is used mainly for passenger service and built for high speeds, and a two-cab locomotive built by the Westinghouse Company for freight service.

As the paper brings out, previous to electrification freight trains weighing about 2500 tons were operated by a Mikado at the head end, a Mallet about two-thirds of the way back, and another Mallet at the rear behind the caboose. At the present time there is placed an electric locomotive and a Mikado type steam engine at the head end and an electric locomotive about two-thirds from the head end of a train of 3500 tons. Originally the speed of trains with steam operation was around 6 to 9 mi. per hr. At the present time trains are handled at 15 mi. an hr., but due to the power situation the demand is limited by restricting the speed to 10 or 11 mi. per hr.

Originally there was a delay at Scenic of from ½ to 1½ hr. to take water on three steam locomotives, a further delay at Tye for cutting off two of the Mallets and adding two of the old three-phase locomotives. I might say that we have been operating for approximately 18 months with two freight locomotives and two passenger locomotives, handling practically all of the traffic over the hill, which requires the power to be in service almost all of the time. We have never yet had to pull a train through the tunnel with the steam engine, due to failure of the electric locomotive. We have had one or two failures of power supply. In that case we had to use steam engines.

A particular point to note about this type of locomotive is its extreme flexibility. The main speed handle controlling the generator field has 29 positions, every one of which is a running position. When the 29th position is reached a closed-circuit transition is made without change in tractive effort, to a connection whereby the traction motors are separately excited from a special field exciter which is driven by the main motor-generator set. The fields of the traction motors are then weakened by decreasing the field excitation of the field exciter, thus further increasing the speed of the locomotive in a number of very easy steps. The locomotive is in this way made to deliver its rated hp. output almost to its maximum speed of 45 mi. per hr.

The separately excited connections are used for regeneration and the method of transition used makes it possible to change these connections easily at any speed either motoring or regenerating and also to change back to the series connection when motoring, without loss of power.

After maximum field strength has been applied to the traction motors in regeneration the main generator voltage may be reduced, making it possible to exert full retarding tractive effort down to 3 or 4 mi. per hr.

In spite of the fact that a large part of the present electrified section is through snow sheds and tunnels giving rise to a slippery rail, the parallel connection of the traction motors enables the locomotive to cling to the rails even under adverse conditions. In case slipping does occur it is only necessary to move the control lever back a few notches to allow the wheels to grip the rail again, resulting in very little loss in speed.

C. E. Carey: I think it is very interesting to go back of the present installation and determine why the motor generator type of locomotive was chosen. Prior to the Great Northern electrification there was only one installation ahead of it, namely the Ford electrification, and this was largely in the experimental stages.

When we consider any electrification we must study it on the basis of the type of service which that railway renders, that is, whether it is a service of heavy trains, slow speed over heavy grades, or whether it is a service requiring high speeds, heavy trains, and over light grades. We must also determine whether or not the service requirements are a combination of these two.

The requirements for the locomotives for the first class of service are high tractive effort, low speed, and flexible operation. The requirements of the locomotives for the second class of service are high speed, high capacity, and high tractive effort with a tremendous amount of power under the locomotive.

A study of the Great Northern system shows that in the Cascades we have very heavy grades which require high tractive effort and slow-speed operation, while between the Columbia River and the Rocky Mountains the country is practically flat, and in the Rocky Mountains again we have heavy grades. So in considering the electrification of the Great Northern a system was chosen which would serve locomotives of both classes.

The motor-generator type of locomotive is one using a system of variable voltage control for the traction motors. Such a system of control has numerous running and regenerating points and is therefore the logical type of control to apply to a locomotive for low speed and heavy hauling operation. The other type of locomotive which requires high speed, high capacity, and high power can only be met with a single-phase locomotive; therefore in the electrification of the Great Northern the 25-cycle single-phase electrification was adopted which provided a system of power supply for both types of locomotives, which ultimately would be required.

I like to look at this sytem of electrification from the angle that it provides a form of energy which puts the work horse and the race horse at their best advantage.

H. R. Morgan: I should like to ask several questions on matters pertinent to this electrification. First, what is the capacity for which the system is designed? We know the Great Northern is looking forward to the future as we did, and we should like to know what they consider the ultimate capacity of their newly electrified section to be. Second, what is the approximate power consumption per gross ton-mile? Under the existing operating conditions, it is highly improbable that the Great Northern has succeeded in getting the highest efficiency out of their system. But they must have some figure and it would be interesting to know what their experience has been to date. Third and last, what is the overall efficiency of their electrified system? We have made quite a few calculations on that ourselves, comparing their a-c./d-c. system to our straight 3000-volt d-c. system, and we cannot agree with them that their system is the most efficient.

H. S. Ogden: The authors have given a rather short discussion on the General Electric locomotive in the paper, but perhaps a more complete description would be appreciated.

The locomotive is a 260-ton 2500-kw. multiple-unit machine of the motor-generator type. It is mounted on the $1 - C + C + 1$ type of running gear. Each of the two trucks carries three motors known as the G. E. 290 that rate approximately 500 hp. The locomotive is 73 ft. 9 in. over knuckles, has a height of 15 ft. 3 in. with the pantograph locked down, and a width of 11 ft. ¾ in.

It has a safe speed of 45 mi. per hr. and a maximum emergency speed of 50 mi. per hr.

On each end of the locomotive is an operating compartment, and back of each of these is an enclosed compartment containing the necessary contactors, reversers, switches, etc. The motor-generator set, of course, takes up most of the space in the cab; near the No. 2 end are located the main transformer and the air compressors. Underneath the motor-generator set coupling is located the traction-motor blower set that supplies cooling air for the traction motors.

The motor-generator set is a five-unit four-bearing set that operates at 750 rev. per min., having a 3500-hp. single-phase synchronous motor that drives the two 1250-kw. 750-volt d-c. generators. Overhung on the No. 1 end of the shaft is the combination single-phase series starting motor, and regenerative exciter. The other end of the shaft mounts the main 65-volt exciter that supplies power for charging the batteries, operating the control, exciting all the machines and for the lights.

On both sides of the regenerative exciter are located the two high-speed d-c. circuit breakers for protecting the traction motors and the d-c. generators.

The main transformer is a 3285-kv-a. air-blast transformer, 11,000/2300 volts, with a small 150-volt tertiary winding for operating the starting motor. This transformer is cooled by two

$6\frac{1}{4}$-hp., 540-volt induction-repulsion motors that drive single-runner fans.

In order to compensate for conditions of low trolley voltage there are two normal running taps that may be used to supply the synchronous motor. Changing from one tap to the other is accomplished under load automatically, this being controlled by means of a sensitive potential relay.

Between the transformer and the No. 2 end contactor compartment are located the two 100-cu. ft. air compressors. These are driven directly from the main transformer from a low-voltage tap. These deliver air for the air-brake system, and for the air-operated control apparatus.

The control equipment of the locomotive is made up of air-operated contactors, switches, and reversers. These take care of the traction-motor and synchronous-motor circuits. There is no oil switch. Protection is afforded by the track substation breakers and a pantograph-lowering relay that in case of trouble in the main transformer will lower the pantographs and lock them down after the substation breakers have opened the circuit. There are also quite a few magnetic contactors on the locomotive, notably those in the main regenerative exciter field, compressor, and motor circuits.

The engine can be controlled from either of the two operating compartments which are identical. The control is centered at each engine man's position, that is, on the right-hand side of the locomotive. Here is located a two-story master controller, the straight and automatic air-brake valves, the control of the motor-generator set and its auxiliaries, along with the necessary gages, meters, sanders, etc. These are conveniently situated with respect to the engine man. The master controller as noted above is a two-story affair, the bottom containing the drum that controls the main generator field and the upper the drum that controls the regenerative exciter field. The former drum is known as the speed drum as it has direct control on the speed of the engine whether regenerating or motoring. The latter drum is known as the braking drum, as it has direct control upon the braking effort of the locomotive by controlling the field strength of the traction motors. There is also a forward and reverse lever. All of the above levers are mechanically interlocked against false and improper operations.

In starting the locomotive it is only necessary to push the motor-generator starting button. This operates contactors that connect the starting motor to the 150-volt tertiary winding of the main transformer. When the set reaches approximately 80 per cent speed a potential relay connected across the terminals of the main exciter picks up, connecting the stator of the synchronous motor to the 1800-volt tap on the main transformer. Then both the synchronous motor and the starting motor pull the set up to speed. As soon as it locks in step the synchronizing relay, which determines synchronism by becoming de-energized when the pulsations in the field-discharge resistor circuit die out, applies excitation. This operation starts a magnetic time-delay relay functioning that allows about five seconds to elapse before disconnecting the synchronous motor from the 1800-volt tap and connecting it on to the 2300-volt tap corresponding to normal operating voltage. The purpose of the time delay is to allow sufficient interval for the field to build up. The locomotive is then ready for service.

Locomotive movement is controlled by varying the field strength of the main generators. This is varied by means of the master controller that operates the small magnetic contactors which operate on the resistance in the field circuit. Weak-field motoring and the consequent higher speed is obtained by shunting the traction-motor fields by a special connection of the balancing resistors. The fields are reduced in two steps to 50 per cent of their normal values in order to obtain the maximum speed of the locomotive.

The traction motors are made to regenerate by separately exciting them by means of operating the starting motor as a d-c. generator. This combination machine has been mentioned above. Current is circulated in the proper direction through the traction-motor fields and balancing resistors and is directly under control of the operator who varies it at will by operating the braking handle of the master controller. The braking drum operates magnetic contactors in the field circuit of the exciter.

This type of locomotive has very flexible control under all operating conditions and it is possible to regenerate practically to a standstill without trouble.

A. W. Eshelby: Mr. Morgan has raised the question of the overall efficiency of the Milwaukee 3000-volt d-c. system as compared with the Great Northern. Inasmuch as there are so many parasites on the power supply it is very difficult as yet to get any definite overall efficiency figures for actual service. When the new tunnel is completed and the present construction load is eliminated from the power system, it will be possible to answer his question satisfactorily. It must be remembered that the tunnel supply has much to do with determining the cost of power.

One feature that should be stressed in discussing the motor-generator type of locomotive in comparison with the d-c. locomotive using series traction motors, is the perfect control that the operator has over his locomotive-wheel slippage. With the straight parallel motor connection used on the Westinghouse motor-generator locomotive, it is possible to slip wheels at any speed desired by the operator and should undesired slipping occur, due to poor track conditions, it is only necessary to back off a notch or two, until slipping stops.

With the series connection used on all d-c. locomotives, and some motor-generator locomotives, when slipping occurs it is necessary to throw off all power and start over again. When this happens in a heavy train with several locomotives, if any one locomotive throws off power to stop slipping, the slipping is usually transferred to the other locomotives. As a result of this the practise on such locomotives is to allow the slipping to continue until the track condition changes rather than throw it over on the other locomotives.

R. E. Kistler: (communicated after adjournment) In a-c. electrifications such as the Great Northern, the problem of inductive interference with paralleling signal lines is an important one. In order to limit these effects the Great Northern moved their open-wire telegraph lines from their right-of-way to adjacent highways. Some tests were made of the induction on signal wires on the new and old lines. These test data indicate that the induced voltage to ground at 1500 ft. separation was about 4 volts per mile per 100 amperes of trolley current or about 30 per cent of the induction at 50-ft. separation. Tests through the old tunnel where the signal circuits are in submarine cable with the armor grounded gave values comparable with those obtained in open wire at 1500 ft. separation. In order to limit induction on the telegraph lines through the new tunnel it is planned to carry the lines in cable placed in iron pipe.

Power Supply for Railway Signals
and Automatic Train Control

BY C. F. KING, Jr.[1]
Associate, A. I. E. E.

Synopsis.—This paper deals, in a general way, with the several systems of automatic block signaling, particularly the a-c. system, and the apparatus commonly used to insure continuity of power supply. It covers briefly the older phases of the subject and more specifically the later applications.

The most modern system of continuous inductive train control, the code system, has required the development of frequency-converting apparatus for this use. Within the past three years, a number of frequency-converting automatic substations has been installed by the railway companies. The class of apparatus used in these stations is discussed, including some details of installations on the Pennsylvania and Long Island Railroads.

AUTOMATIC block signaling on railroads has reached a high degree of perfection. Within the last few years train accidents due to failures of signals to operate properly have been practically unknown. Developments were started many years ago but perhaps the greatest impetus toward developing and applying the automatic signals came in 1922 when the Interstate Commerce Commission ordered 45 railroads each to equip one locomotive division with automatic train control or train stop. In 1924 a second order was issued calling upon 41 of the original 45 carriers to equip a second locomotive division. These two orders covered approximately 15,000 track mi. and 6300 locomotives. All of this work has been completed.

The experience gained in this widespread use of the automatic system has been very valuable and has led to the development of the modern reliable signal equipment.

The most important early development was the adoption of the closed-track-circuit principle. In this system absence of current in the track causes indication of the low-speed or stop signal. This makes for safety and this principle is the basis of all modern systems.

For a-c. signaling the track circuit consists of the rails, rail bonds, track relay, and track transformer. For d-c. signaling, primary cells or storage cells take the place of the track transformers.

There are also two combination systems using both alternating current and direct current known respectively as the a-c. floating-battery system and the a-c. primary-battery system. These systems utilize direct current for the track circuit under all conditions. Normally, alternating current is used for the lamps which give the position-light and color-light signals. If the alternating current fails the lamps are connected quickly to a battery by means of an automatic change-over switch or "power-off" relay. There is, in effect, an automatic substation of the order of 150-volt-amperes capacity at each signal location.

The fundamentals of these systems and the fundamentals of the d-c. system are such as to provide excellent insurance against signal outages due to power failures, if the batteries are properly maintained.

A-c. signaling owes its development to the application of automatic signaling on d-c. electric-traction systems and to difficulties encountered on steam railways caused by interference with d-c. track circuits by stray currents from nearby d-c. circuits.

For the operation of a-c. signals the practise is to provide a power line paralleling the railway. At each signal location the line voltage is stepped down to the proper voltage for the track circuit, relays, lamps, and semaphore mechanisms.

Power for operating the early a-c. signal systems was provided by means of steam-engine or turbine-driven alternators operated by the railways. The switching was performed manually and two attendants were always on duty, one to fire the boilers and one in charge of the engine room. When synchronizing the alternators, the fireman manipulated the throttle and the engineer operated the switchboard. These power plants were located along the right-of-way, consideration being given to the division of load among stations and the possibility of locating the signal apparatus in plants, such as shop power plants, where the labor was already available.

At the present time railway companies realize the advantages of purchasing power from central station companies with the result that the isolated plants are rapidly being replaced by unattended automatic substations supplied from power company lines.

It is well known that the cost of central station electric power has declined during the past decade. Public utility lines have been extended so that power can be purchased in almost any locality. Outages of considerable duration are exceptional. At the same time the cost of generating power in isolated plants has increased.

Automatic switchgear may be obtained to perform practically any function that can be performed manually and to do it more reliably and more quickly. Switchboard operators may, therefore, be eliminated.

To provide a degree of reliability for a-c. signaling

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comparable with the reliability of systems using batteries, it is necessary to provide two sources of power supply for each section of signal line. These sources of supply are usually at opposite ends of the line and the switchgear provides for one of the sources to be feeding at all times and for the other to be connected quickly to the line upon failure of the normal or preferred source. Protective relays are provided which make it impossible for both sources to be connected to the line at the same time, also low-voltage protection to disconnect the signal line from the source of supply in the event of loss of voltage on the supply, and over-current relays to disconnect the signal line from the supply in the event of heavy overloads on the signal line.

The signal power supply on the Florida East Coast Railway between Jacksonville and Miami is an excellent example of this type of installation. Over the 366 route miles between Jacksonville and Miami, eight automatic substations are located. Between Jacksonville and Daytona Beach the voltage is 4400, and between Daytona Beach and Miami the signal line voltage is 2200.

A large majority of the present automatic train control and train stop installations are of the intermittent inductive type or the continuous inductive type. The intermittent inductive type is effective only at wayside signal locations. No power is required for the wayside elements, or inductors as they are called. The continuous inductive type provides continuous cab-signal indications. It is effective regardless of the location of the train in the block. It makes use of a track circuit superimposed on the wayside-signal track circuit.

The code system is the latest development of the continuous inductive system. In this system the receiving circuits on the locomotives are "tuned" so that they will respond only to energy supplied at a certain frequency. To eliminate the possibility of interference from commercial power circuits a nominal frequency of 100 cycles has been widely selected as the most favorable frequency for the track-circuit current.

Railways using the code system are the Pennsylvania, the Long Island, the West Jersey and Seashore, the Central of New Jersey, the Reading, the New York, New Haven & Hartford, and the Delaware, Lackawanna and Western. Some of these present interesting track-current conditions. The Long Island has direct current for propulsion, 25-cycle current for wayside signals, and 100-cycle current for automatic train stop. The Pennsylvania between Altoona, Pa. and Harrisburg, Pa. has 60 cycles for wayside signals and 100 cycles for train stop, and on the Pan Handle Division, Pittsburgh, Pa. to Newark, Ohio, 100 cycles for both signals and train stop. The D. L. & W. uses direct current for wayside signals and 100 cycles for train stop between East Buffalo, N. Y. and Elmira, N. Y., and 100 cycles for both wayside signals and train stop between Elmira and Johnson City, N. Y.

Rotating apparatus must be provided to change from 25-cycle, 60-cycle, or d-c. primary supply to 100-cycle output. The machines may consist of d-c. motors, synchronous motors, single-phase or polyphase induction motors driving synchronous alternators, or of induction motors driving induction generators.

With the exception of very unusual conditions (as on the Long Island which will be described later) the choice is usually between (a) squirrel-cage induction motors driving synchronous generators with direct-connected exciters and (b) squirrel-cage motors driving induction generators.

Induction generators cost less than synchronous generators. Part of the power output is obtained by transformer action between the stator and rotor of the generator. With a 60 to 100-cycle conversion, 60 per cent of the power output is obtained by transformer action and the driving motor need be large enough to supply only the remaining 40 per cent plus the friction and windage. There are characteristics, however, such as low-power factor, changes in secondary voltage in direct proportion to changes in primary voltage, and inability to adjust the voltage over a wide range by means of a rheostat as can be done with a synchronous generator, that probably will limit the induction type to the smaller ratings and to applications where the high-frequency track circuit is used for train control only.

One of the divisions ordered by the Interstate Commerce Commission to be equipped with automatic train control was the Pan Handle Division of the Pennsylvania Railroad. This division extends from Pittsburgh, Pa. west to Newark, Ohio. It consists of 158 route miles and 375 track miles over which there are operated an average of 233 trains a day.

For this division the code system of continuous inductive train stop with "forestaller" was adopted. Four locomotive cab-signal indications were provided, the three fundamental signals, *viz.*, "proceed," "proceed with caution," and "stop," and a fourth signal indicating that the approach to the next block must be made at restricted speed. To "forestall" an automatic brake application each change in the cab signal indicating a less favorable condition ahead, must be acknowledged by the engineman within six seconds. The acknowledgment is made by momentarily reversing a conveniently located switch and then returning it to normal.

At the same time the automatic train stop was installed, manually operated and d-c. semaphore signals were replaced with a-c. position-light signals.

To provide 100-cycle energy for the wayside signals and automatic train stop, eight automatic substation equipments were installed. The accompanying diagram, Fig. 1, indicates the relative locations of the equipments.

At Newark, Coshocton, and Dennison 60-cycle energy is purchased from the Ohio Power Company and the equipments are located in Ohio Power Company substations. At Weirton Junction and McDonald, power is purchased from the West Penn Power Company, the equipment at McDonald being located in a substation of the power company. At Pittsburgh, power is purchased from the Duquesne Light Company. Substations were built along the right-of-way to house the equipments at Pittsburgh and Weirton Junction. The railroad company has a large freight locomotive terminal at Scully and the facilities include a power plant with generating apparatus. This provided an excellent location for one of the signal-power apparatus units.

At all of the above mentioned stations the frequency-converting apparatus consists of a 75-hp., 2200-volt, three-phase, 60-cycle squirrel-cage induction motor direct-connected to a generator rated 60 kv-a. 80 per cent power factor, 220 volts, 100 cycles at 1200 rev. per min. single-phase with a direct-connected exciter. The motors were designed to carry full load with normal voltage impressed on their terminals with a slip of not more than two per cent of synchronous speed. This insures an output frequency of not less than 98 cycles.

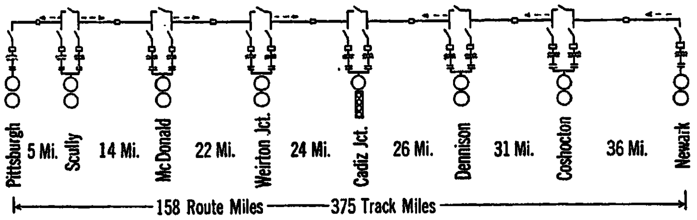

FIG. 1—ARRANGEMENT OF AUTOMATIC SIGNAL SUBSTATIONS PAN HANDLE DIVISION, PENNSYLVANIA RAILROAD SYSTEM

An exception to the rule regarding the purchase of current from public utility companies was encountered at Cadiz Junction, where satisfactory service was not available. Therefore, a gasoline-engine-driven generator was installed. The engine develops 100 brake hp. at 1000 rev. per min. The generator is rated 50 kv-a., 80 per cent power factor, 220 volts, single-phase, 100 cycles, 12 poles. A 15-hp., 100-volt starting motor, operating from a storage battery, cranks the engine and brings it up to speed before the engine takes the load. The motor is located between the engine and the generator. The exciter is direct-connected to the other end of the generator shaft.

Several schemes of operation are possible with the apparatus provided for the Pan Handle Division. The scheme that was decided upon as offering the most advantages from both the economic and operating points of view was for all stations, except Cadiz Junction and Pittsburgh, to be in service under normal conditions. Newark feeds east to Coshocton; Coshocton feeds east to Dennison and Dennison feeds east to Cadiz Junction. Weirton Junction feeds west to Cadiz Junction, McDonald west to Weirton Junction. Scully feeds west to McDonald and east to Pittsburgh. At all stations the 100-cycle voltage is stepped up to 6600 volts for transmission, a pole line having been built the length of the division for the special purpose of taking care of this single-phase power line.

If the voltage fails on the line between Newark and Coshocton the contactor on the west feeder panel at Coshocton instantly closes and restores voltage. In like manner a voltage failure between Coshocton and Dennison provides the impulse for instantly closing the signal-line contactor on the west feeder panel at Dennison. The gasoline engine generator set at Cadiz Junction is used only for emergency service. It is, like the motor-generator sets, fully automatic in operation. Starting impulse is received in the event of a voltage failure on the signal line between Cadiz Junction and Dennison or Cadiz Junction and Weirton Junction. It starts and takes the load in less than six seconds. A line-voltage failure between Weirton Junction and McDonald causes the contactor on the east feeder panel at Weirton Junction to close instantly. A failure at Scully causes the east feeder contactor at McDonald to close and provides the starting impulse for the emergency motor-generator set at Pittsburgh. A clapper-operated oil switch connects the motor to the 65 per cent tap of an auto-transformer for starting and a solenoid-operated oil switch (the solenoid being energized from the exciter) connects the motor to full voltage. Starting in this manner it requires, depending principally upon bearing temperatures and voltages of the primary supply, from five to six seconds to restore voltage to the signal line. The motors are started through auto-transformers. They were designed, however, for full voltage starting under which condition the time required to restore voltage on the signal lines could be reduced somewhat.

Transfer of load from any station to an adjacent station may be made in less than one second. For example, to transfer the load on the Newark Station to Coshocton it is necessary only to depress a button on the feeder panel at Newark causing the signal-line contactor to open. The loss of voltage on the signal line, as previously stated, provides the closing impulse for the west feeder contactor at Coshocton.

In the event of signal-power line trouble it is important to segregate the defective section as quickly as possible. On the Pan Handle Division a pole-mounted oil circuit breaker is located approximately midway between each pair of adjacent substations. These breakers are set to open instantly on short circuit. If a short circuit occurs on the side of the breaker farthest away from the station feeding the section, the breaker opens instantly and sectionalizes the line. If the trouble occurs between the breaker and the station feeding the line, the line contactor on the feeder panel opens after an appreciable time depending upon the setting of the controlling relay. The loss of voltage provides the closing impulse for the corresponding feeder contactor in the adjacent station. The instant this contactor closes the oil circuit breaker opens and sectionalizes the line. At the west end of the division, where the traffic is relatively light as compared with the east end, there is a possibility of 18 mi., or half the distance between Newark and Coshocton, being out of service due to line trouble. Eastward the distances are shortened until, between Scully and Pittsburgh, there is a possibility of 2.5 mi. being automatically segregated because of line trouble.

Manually operated, two-way disconnecting switches are located one at each signal location for further sectionalizing the line. The signals average approximately one per mile east of Dennison and one for every five to ten thousand feet west of Dennison.

Additional flexibility is obtained by the use of a two-pole, manually remote-controlled, gang-operated pole-top disconnecting switch at each substation which provides means for tying together any two adjacent sections of the power line.

With generating apparatus, such as is used on the Pennsylvania, supplying current for both signals and train control, automatic voltage regulators are used. Overvoltage does not make for a dangerous condition in so far as the train control is concerned but it does provide a dangerous condition in connection with the operation of the wayside signals. This is because overvoltage may provide so much current in the track circuit that sufficient current will not be shunted by trains to deenergize the track relays. If automatic voltage regulators are not properly maintained the contacts may, in time, stick, which will result in excessive voltage. Provision should be made for either automatically removing the generator from service or automatically inserting a fixed resistor in the exciter field sufficient to reduce the voltage to a safe operating value.

Provision is made for opening the signal-line contactors on short circuit. If the station is an end station, such as Newark or Pittsburgh, and, therefore, has only one line contactor, the motor-generator set will shut down and will be automatically locked out of service if the contactor opens due to short circuit. If the station has two feeders, both line contactors must be opened before the machine will be automatically locked out of service. Overloads which if of short duration will do no damage but, if sustained for a considerable time, will result in trouble, cause thermal relays to function and remove the motor-generator set from service.

Other features, such as reverse-phase protection for the motors, reclosing of line contactors a definite number of times after opening on short circuit, before finally locking open, and annunciator relays to indicate to the maintenance man the protective relay that has functioned, are incorporated in this class of substation apparatus if warranted.

Another modern installation of automatic signals is located on a branch of the Long Island Railroad. This installation is interesting on account of one unusual feature as already mentioned. The unusual feature consists of a d-c. driving motor in the motor-generator set instead of the more usual a-c. motor. It was not possible here to use an a-c. motor because the frequency of the main a-c. supply varies so much that the signal frequency would vary beyond the permissible limits of 96 and 100 cycles.

In this installation the Long Island Railroad has automatic train stop between Jamaica and Babylon, a distance of 27.6 mi. An alternator for providing 100 cycles is located in each of the substations which house the electric-traction synchronous converters at Babylon, Lynbrook, and Jamaica. Lynbrook is 8.3 mi. east of Jamaica and 19.3 mi. west of Babylon. The motor-generator sets at Babylon and Lynbrook are four-unit machines. The driving motor is rated 20 hp., 650 volts, direct current. It is direct-connected to the 100-cycle alternator, an exciter, and a pilot generator. The alternator is rated 15 kv-a., 220 volts, single-phase, 100 cycles at 1500 rev. per min. The exciter is rated 1 kw., 125 volts. The pilot generator is rated 0.5 kw., 250 volts direct current.

The receiving circuits of the steam locomotives and multiple-unit cars are tuned for best results at 98 cycles. The efficiency of reception decreases as the frequency changes in either direction from normal, the permissible limits of frequency being 96 and 100 cycles. The motors are operated from the 650-volt d-c. busses which also supply energy for the multiple-unit cars. As the bus voltage may vary between 450 and 700 a speed regulator had to be provided. The pilot generator operating in conjunction with a simple and sturdy vibrating regulator accomplishes the desired results.

The regulator consists, principally, of a stationary coil and magnetic circuit and a movable coil in series with the stationary coil. The movable coil is suspended on a knife edge in the magnetic field. When the voltage of the pilot generator is 250, which it is at normal speed, the movable coil is in mid-position and the contact on the arm attached to the coil is midway between two stationary contacts. If the speed of the motor increases, the voltage of the pilot generator increases and the movable coil takes such a position as to bring together the contact on its arm and one of the stationary contacts. This strengthens the motor field by shunting the field rheostat through a fixed resistor. If the speed falls below normal a spring pulls the movable arm in the opposite direction and draws together the movable arm contact and the other stationary contact, which weakens the motor field by shunting it through a fixed resistor and the speed increases. The contacts are made of high-grade graphite, 1⅜ in. in diameter. They will not stick and they have long life.

Under normal operating conditions the alternator at Lynbrook feeds east to Babylon and west to Jamaica. The 100-cycle voltage is stepped up to 2200 volts for transmission. The alternators at Babylon and Jamaica are for emergency service only. The switching in all stations is performed manually. As attendants are present to supervise the electric-traction synchronous converters and as all stations receive their primary

25-cycle energy from the same source, little benefit would be obtained from automatic switchgear.

CONCLUSION

Automatic block signals are established firmly as necessities on those railways where they are installed and where operations are planned so as to take advantage of the safety and dispatch which the signals provide. Relatively simple, automatic substations used in conjunction with the a-c. systems, when the frequency of the signal energy is the same as the frequency of the primary supply, will be employed in increasing numbers as signaling systems are extended.

The future of the frequency-converting substation is not as certain. The 100-cycle current is primarily for train-control operation. All of the installations ordered by the Interstate Commerce Commission have been completed. Whether additional orders will be issued and whether the carriers on their own initiative, will make additional installations are open questions. In any event, the frequency-changing motor-generator sets in ratings of 1.5 kv-a. to 60 kv-a. and the accompanying switchgear, that have been installed in the past three years, are interesting additions to the steadily increasing electrical facilities of our railway transportation systems.

Discussion

E. F. Pearson: The statement is made in this paper that transfer of load from any station to an adjacent station may be made in less than one second.

In order to perform this operation it appears that three or four relay operations and two contactor operations are necessary. If we add together the time increments necessary for the various relaying and contactor operations it would appear that the operation would take considerably longer time than one second, and I, therefore, question the accuracy of this statement.

L. J. Corbett: In the early days of the automatic train-control systems, when the Interstate Commerce Commission issued its order on the matter, some of us in the inductive-coordination work saw a cloud on the horizon. The early systems developed used the commercial frequencies of 25 and 60 cycles, and it was found that when power lines of such frequencies paralleled railway lines equipped with these systems, induction from the power lines could sometimes cause wrong signals in the cabs of the locomotives. Such a condition would have added another obstruction to the placing of power lines along railways, and the right-of-way man would have had a more difficult time in all later constructions.

Fortunately, however, due to the agitation by men who saw the induction difficulty, and also to the cooperation of the railroads and the signal manufacturers, who departed slightly from their earlier competitive policy in producing the control systems, there was introduced that additional link,—the transformation from the commercial frequencies of 25 and 60 cycles to one which insured freedom from inductive interference. The 100-cycle control systems now standard will not be adversely affected by any harmonics of 25 or 60 cycles. This was a big step in this development, and we watch with interest its continued progress.

C. E. Carey: Mr. Pearson questioned the length of time required to restore voltage to the line. The time required to depress the button and the time for the feeder contactor to open are not included in the "less than one second" required to transfer the load from any station to an adjacent station. The loss of voltage on the line, following the opening of the feeder contactor in the station dropping the load, causes a low-voltage relay in the station at the other end of one of the adjacent sections to close its contacts. This closes the circuit to the operating coil of a feeder-contactor control relay, which relay functions to close the circuit through the operating coil of the feeder contactor. The feeder contactor closes and voltage is restored to the line. By as careful timing as possible, with a split-second stop watch, it was found to require 0.9 sec. to restore voltage.

T. S. Stevens: (communicated after adjournment) I am not at all certain that the first paragraph is true. The Union Pacific has been equipped with automatic signals long before 1922. It is probable that the largest mileage of automatic signals was installed after this year, but I do not remember that the development was dependent on the train control order by the Interstate Commerce Commission. In fact I know of several instances where the installation of automatic signals was postponed until the policy of the Interstate Commerce Commission had been established.

The description of the track circuit does not bring out the essential feature of a closed track circuit. The absence of current in a track circuit is an abnormal condition. Ordinarily the circuit is closed continuously. The display of a stop signal is caused by the current being shunted away from a relay through the wheels of a train.

Frequency changers have been in service on the Santa Fe for about twenty years. They are used to obtain a 25-cycle current from a 60-cycle commercial supply in order to take care of the higher power factor of the 25-cycle current used on track circuits which results in a longer length of track circuit than could be obtained by the use of 60 cycles. It is probably true that with the development of all a-c. relays the efficiency of these devices has been increased to such an extent that if the installations were made today it would not be deemed necessary to provide 25-cycle current.

C. F. King: In answer to the communication from Mr. T. S. Stevens received after adjournment of the meeting, I wish to call attention to the fact that during the five-year period January 1, 1923 to January 1, 1928 there were installed 17,379 route-miles of automatic block signaling on the railroads of the United States and Canada. Probably 3 per cent of this mileage was on Canadian roads. This was, by far, the most active five-year period of automatic-signaling installations in the history of our country. This period of great activity occurred immediately after the automatic-train-control orders of the Interstate Commerce Commission were issued and it does not appear unreasonable to conclude that these orders were not entirely in the background when consideration was being given to installations of automatic signals on much of the above mileage. The figure of 17,379 was obtained from "Railway Signaling," issue of January 1928.

The purpose of the statement that "absence of current in the track causes indication of the low-speed or stop signal" was to point out that the fundamental principle of automatic signaling systems, *viz.*, the closed track circuit, protects against abnormal conditions such as "absence of current in the track" which may be the result of a broken rail. The paper was prepared to deal particularly with the power supply apparatus and the discussion of the signals was purposely made as brief as possible. Paragraph three probably was made too brief.

Mr. Stevens states that frequency changers have been in service on the Santa Fe for about 20 years to obtain 25-cycle current for track circuits from a primary 60-cycle supply. It is not claimed that rotating apparatus of this class is, essentially, new. It is the frequency, *viz.*, 100 cycles, which attaches the principal interest, if any, to the frequency changers discussed in this paper.

Automatic Mercury Arc Power Rectifier
Substation on the Los Angeles Railway

BY L. J. TURLEY[1]
Associate, A. I. E. E.

Synopsis.—*The development of the commercial mercury arc rectifier is outlined briefly in this paper and there are given the advantages which led to its adoption in a double-unit automatic station recently installed by the Los Angeles Railway. A report is made of the very satisfactory operation which has resulted. A description of the station is given and methods of operation and maintenance are presented.*

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INTRODUCTION

On reviewing the various epochs of the historical development of the mercury arc rectifier, commencing with the experimental work of Peter Cooper Hewitt in 1902 and covering a period of twenty years, one is at first amazed at the slow rate of progress of American manufacturers toward perfecting such an equipment as compared with that usually observed in the development of similar important modern productions. For ten years prior to the war, the manufacturers seemed to confine their research to the theory and problem of proper vacuum maintenance, vacuum seals, and temperature allowances, apparently without reaching a complete and satisfactory solution. Naturally, a general state of apathy existed during the war; while with the few years immediately following, the reluctance to concentrate their efforts toward a final solution, sufficient to start production, may be attributed largely to the enormous demand for immediate delivery of rotating apparatus required to meet the general expansion and growth of the various electric industries. Sound engineering expediency seemed to give way to the exigency arising from aggressive commercial expansion.

Meanwhile, the European manufacturers developed a type of rectifier that followed the established principles common to early American designs, and gave sufficient service satisfaction in the foreign field to invite its introduction into this country for an apparent and ready market. Simultaneously, the enterprising spirit of American manufacturers was prompted to activity in finishing its original design, to the extent that production was started, followed by a rigid field service test to meet all preliminary requirements, and resulting in the creation of a pronounced interest and demand in the field of prospective users.

Although the basic structure of present day rectifiers shows no radical or marked advance over early developments, still a variety of problems arose, not only with respect to the design, but involving the protection and operation of this type of apparatus. These broadened the field of exploration for considerable added and novel improvements—especially with the auxiliary equipment. The speed of all this accomplishment has been reflected in a final solution as embodied in the present type of rectifier now under discussion. Thus, during the last three years, we have witnessed many pioneer installations of European and American makes of equipment, scattered on diversified railway loads, that have shown a rapid growth in popularity and have produced a considerable degree of confidence, due to the rectifier's general simplicity, compactness, and reliablity.

As greater familiarity with this equipment developed, many other important factors in its installation and operation appealed to the operating engineer. A study of conditions that entered into a problem for a specific class of application, and the results from its short time operation, placed this rectifier in a favorable position and demonstrated its relative advantages in its supplementing synchronous converters, where such application involved load centers of low load factor and heavy momentary peaks.

Finally, its insensitiveness to short circuits; its adaptability to full automatic control; its comparative noiselessness in operation; its ability to carry sustained short time overload; its absence of moving parts, excepting small auxiliaries; and the elimination of the attending troublesome features commonly experienced with the operation of large rotating machines, all substantiate the claims advanced by its proponents and constitute such valuable and economical assets as obviously to insure for the rectifier a most favorable recognition by the more enterprising engineers of the railway industry.

There are a few apparent disadvantages. The penalty of considerably lower power factor may be serious with some installations, but this is more than offset by a high and favorable all-day efficiency factor, when based on over-all conditions, in comparison with a synchronous converter installation of similar rating and operating under similar load requirements. The complaints from sections, of interference with communicating circuits, are comparatively few and are fast disappearing. The characteristic high harmonic voltages, as generated by a rectifier, are subject to correction at very little expense. Suitable and satisfactory mitigation of ad-

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verse noise units have been applied through the cooperative measures instituted by utilities and manufacturers, to the complete elimination of all such contentions. Surely, the 10 to 15 per cent higher first cost over synchronous converters would seem to be justifiable only to cover a certain amount of development cost common to all new introductions. Usually, quantity productions soon absorb and wipe out the excess in such overhead costs. How soon this lower price is to be realized by the users of this equipment would seem to depend upon the rate with which the manufacturers expand their design and facilities to offer larger ampere capacity units for active competition throughout the entire range of synchronous converter applications. The various economies resulting from the operation of rectifiers will then accrue to the operating companies in amounts of substantial proportions.

The numerous papers on this subject published during the last few years have dealt mainly with the theoretical principles applied to or developed from the initial and subsequent design of the mercury arc steel rectifier of relatively small capacity. Only recently we have been given information on actual performance of a few installations of 1000 kw. capacity. Throughout this outline we will draw deductions from comparisons with the synchronous converter. We will not touch upon the fundamental theories of this type of apparatus, nor attempt an explanation of its physical phenomena, but present important factors that led up to the decision in favor of this type of equipment, and give added proof of the rectifier's satisfactorily meeting a railway load requirement, as gained from our experience with a short time operation of the double-unit automatic substation recently installed by the Los Angeles Railway in Inglewood, near the City of Los Angeles.

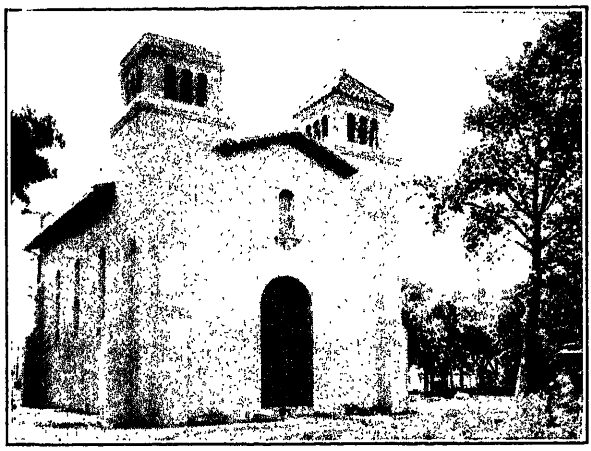


Fig. 1—Inglewood Substation

General Description of Building and Equipment

Situated in a beautifully parked ground, the exterior of this steel framed, reinforced concrete building, with its amber colored glass windows, large arched doorway, heavy tiled roof, and double belfry towers, presents a striking similarity to a chapel of typical Spanish architecture. It was purposely designed as such, to meet the architectural harmonies of adjacent buildings. Fig. 1 shows exterior view of the building. The blind windows and small entrance door, suitably fitted, prevent the entrance of dust, except as it may be carried through the regular air channels, which are provided with air filters. No extra expense was incurred toward soundproofing against what little noise or hum might develop from the operation of the totally inclosed apparatus.

The interior of the building is artificially lighted, effectively air cooled and has plastered walls painted white. The equipment consists of a double 500-kw. unit complete with separate three-phase power transformers, interphase transformers, reactors, rectifier tanks, vacuum pumps and switchboard, the protection and operation of which are under full automatic control. The feeder panels are similar to the standard automatic high-speed circuit breaker equipment and control scheme as installed in other automatic substations on this railway property. On the main floor level, on either side of the entrance, is located the transformer compartment of each unit, while in the main room a rectifier has been placed to each side of the aisle-way, with switchboard facing same at the rear of building. Above are consecutively arranged on a double gallery and in switching rooms, the double 15-kv. high-tension entrance lines, lightning arresters, busses, and oil circuit breakers. Figs. 2 and 2A give an interior view of the station, showing position of rectifier and switchboard section.

Certain layout of equipment in building might require greater or even less space allowance for the rectifier; but with this application the width of building was determined largely by the length of switchboard and height by state law clearances, while the building length was due to the 15-kv. equipment and bus line, all of which would have been the same area and length whether for 500- or 1000-kw. double-unit installation of the synchronous converters or rectifiers.

Application

The decision to apply rectifier equipment with automatic control resulted after considerable study, the analysis being carried out in some detail, an abstract of which may be of some interest.

The entire length of railway line to be fed from this station, extends over six miles beyond the intermediate section of the railway system. Fig. 3 shows map layout. Formerly this line received its power from the small 25 year old manual station, consisting of three small units and located within 2000 ft. of the site of the new substation. Due to other developments, both old building and equipment had to be abandoned and removed. Except for special events, the car service normally rendered had a peak headway of four min., graded to 25 min. for lighter load periods. The low average energy consumption and the resultant low station load factor, coupled with intervals of 30 to 60 min. between load demands during early morning hours, which would create a possible frequency of starting and stopping of station equipment, were essential factors of operation that gave the rectifier more favorable comparison in applying its electrical characteristics as to efficiency, readiness to serve, and simplicity in starting.

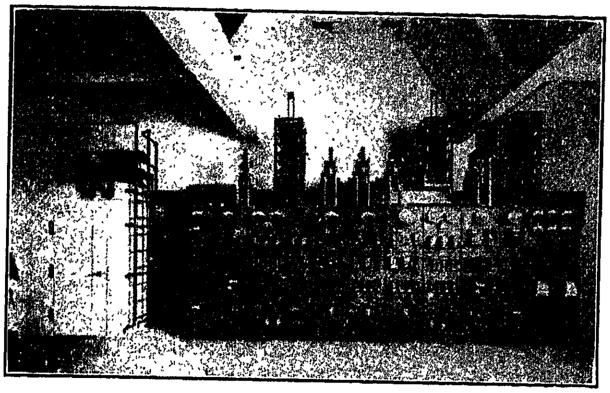


Fig. 2—Switchboard for Double Unit and Three Feeders

Further, there was a commendable interest on the part of the railway company in assisting the industry in pioneering this new introduction with a practical application. Provisions have been made to keep necessary records on results of operation, so as to verify all claims as before set forth and those claims that are expected to be proved as to less frequent inspection requirements, longer periods between overhauling and lower maintenance charges per 1000 kw. installed capacity in comparison with the several automatic synchronous-converter stations of the railway company.

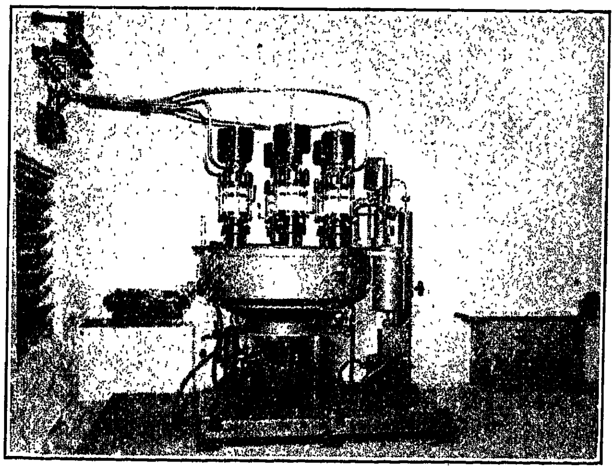


Fig. 2a—Number 1 Unit, 500-Kw. Rectifier

Doubtless a single 500-kw. unit would have been ample in capacity with a slight marginal allowance for future growth; however, in the event of this single unit's failure, normal railway service to this extended line could not have been economically rendered from the next closest substation. The investment in a double unit was considered advisable and followed the liberal policy of the railway company toward guaranteeing the greatest possible safeguard for continuity of power supply and car operation to this important section of its system.

The experience obtained from many years of operation with automatic control applied to synchronous-converter railway substations, naturally led to choosing an automatic application for this rectifier station. It is simple, effective, and surprisingly reliable, and has become generally adopted. Those chief factors that are usually presented in favor of automatic control—improved labor conditions, improved service continuity, and reduced operating expense—may be considered as the salient factors derived from operation of rectifier equipment.

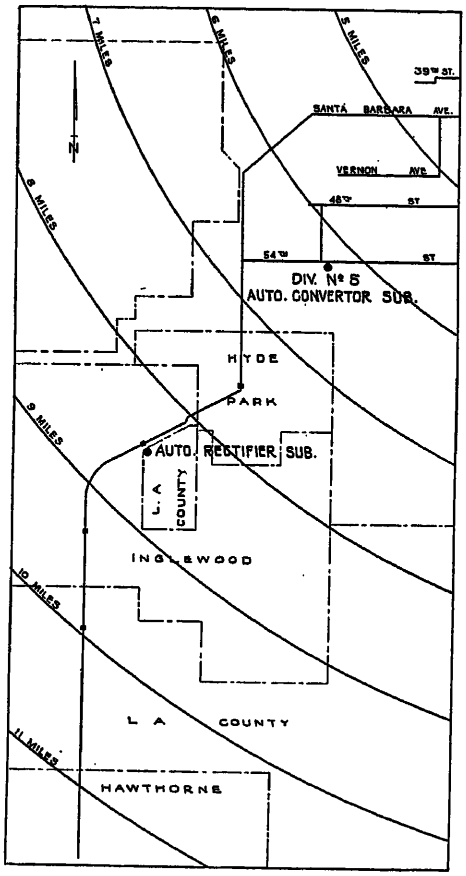


Fig. 3—Trolley Line and Substation Location

The skepticism and doubts witnessed in the early part of full automatic control applications are being repeated with respect to the rectifier introduction and performance. Time alone should efface all such uncertainties.

Weights

It is interesting to note from Table I, which gives approximate weights of various apparatus, including 8000 lb. for interphase transformer and d-c. reactor, the total weight of the rectifier complete installation is only 400 lb. greater than for synchronous-converter units. The rectifier itself weighs one-third that of the converter and did not require any special foundation, except as given by a six inch cement flooring.

TABLE I
COMPARATIVE WEIGHTS

	Converter	Rectifier
Machine	15,000	4,500
Main transformer	14,850	19,500
Starting panel	1,500	....
Interphase transformer	....	4,700
D-c. reactor	....	3,600
Switching equipment	27,000	26,750
Total	58,350	58,750

Rating

With the exception of their momentary load ability, the rating of these 500-kw. unit rectifiers is equal to that of synchronous converters, since they are based upon the same standard method of rating such equipment for railway application. Table II shows this comparison.

TABLE II
COMPARATIVE RATING

	Synchronous converter	Rectifier
Continuous rating—amperes	833	833
Two hour rating—per cent load	150	150
Two hour rating—amperes	1250	1250
One minute rating—per cent load	300	200
One minute rating—amperes	2500	1667

Although a converter would ordinarily carry its two-hour overload rating of 150 per cent load continuously, yet the sustained high temperature would naturally shorten the life of the insulation. On the other hand, the rectifier, exclusive of transformers, could be expected to operate continuously at its two-hour overload rate without shortening its life.

The momentary load of one minute duration allows the converter 300 per cent load and the rectifier 200 per cent load. This difference is attributed to the rapidity with which the maximum allowable temperature rise affects operation. The converter operates through a wide range of temperature allowances. Due to its thermal capacity, a 300 per cent load superimposed for one minute upon its continuous load temperature does not raise the temperature of the hot spots of the machine fast enough to do injury before the load has been reduced. The rectifier works with temperatures of a very narrow range, has low thermal capacity, and is affected by low as well as high temperature. A one-minute load of 300 per cent creates such a rapid rise of temperature that the heat affects the performance, and might damage the anode tips.

The instantaneous overload of a converter is limited usually by its commutating capacity, and when such limits are reached there is a possibility of damage to the machine; locking it out of service, especially if a flashover prevails. The rectifier is not so affected by instantaneous overloads, even of short circuit proportions. Under certain conditions the rectifier may occasionally "arc-back," which results in practically no damage; at least not enough to prevent it going back into operation within a few seconds.

Efficiency

A large amount of the power used by the auxiliary apparatus is foreign to a synchronous-converter installation. The segregation of this power for the six-phase unit at Inglewood is given by Table III.

TABLE III
POWER FOR AUXILIARIES

	Watts
Six, 150-watt heaters for anodes	900
Three, 2000-watt heaters for tank	6000
One, 500-watt heater for condensation pump	500
One vacuum pump, complete	700
One arc striking set, complete	1000
Total	9100

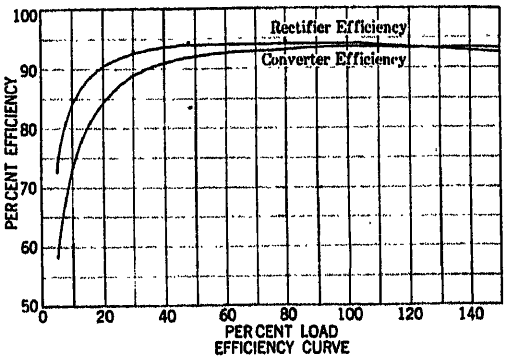


Fig. 4

Under ordinary operation, the 6000-watt tank heaters are seldom in use; and to a slight extent only are the anode heaters and vacuum pump load used. These facts require a comparison of efficiency to be made on over-all conditions. The efficiency of a rectifier itself is practically constant for all loads and considerably higher than with a converter. The drooping characteristic in the efficiency curve for a rectifier unit is largely attributed to the effect of the power transformer. The manufacturer's curve on efficiency, as estimated for this installation, is given by Fig. 4. A certain number of check points is plotted on this curve, as actually obtained by using properly tested a-c. and d-c. watthour meters, which power includes consumption by all auxiliary apparatus. On an average 24 hr. load of 200 kw., each rectifier unit in this substation has an efficiency of 94.0 per cent against 90.0 per cent for a converter of corresponding size. At a lower load factor than at Inglewood station, a greater difference in efficiency would be obtained, which would favor the application for interurban railways.

POWER FACTOR

Although the specific power factor of the rectifier itself has a fairly high value, when measured on the primary of the power transformer, it ranges from 90 per cent to 92 per cent for ordinary loads, reaching as low as 75 per cent at 10 per cent light load. The operating power factor for Inglewood, during the normal 18 hr. range of load, remains about 86 per cent. It is lower than the manufacturer's estimate, doubtless due to the compounding features, the drooping characteristic of the power transformer, and the combined effect of the a-c. supply voltage. In fact, with compound winding, the power factor is about 4 per cent lower than for shunt voltage regulation. Fig. 5 shows power-factor curve as given by meter on primary side of the circuit for shunt and compound operation. The accuracy of such a method of measuring true power factor has been questioned, due to distorted wave form affecting the instrument and giving a much lower indication than the wattless component.

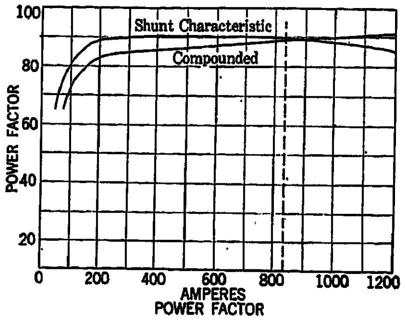


FIG. 5

It is not subject to regulation as with converters; however, the average power factor of this installation is about the same as on portions of the railway system using induction motor-generator sets. Since the railway company has no penalty in contract with the power company on purchase of power, based on kilovolt-ampere demand factor, a lower power factor than that obtained with synchronous converter is not so important an objection, especially with a substation of such small capacity.

REGULATION AND VOLTAGE CHARACTERISTICS

Although the voltage drop in the rectifier proper is nearly constant for all ordinary loads, yet the shunt characteristics of the combined unit of rectifier and transformer is claimed to give about six per cent voltage regulation at full load. This variation was considered with less favor for this particular double-unit application of the Los Angeles Railway since the company's policy is one of maintaining a fairly high uniform trolley voltage along the route of car travel to the outlying districts.

Voltage curve, (Fig. 6) includes regulation for both shunts and compound voltages with this installation. The compound features of the combined unit give a 2 per cent regulation. The a-c. supply voltage is 3 per cent above normal and results in a 3 per cent higher d-c. voltage than originally calculated. To guard against such conditions, it would seem advisable to have one, if not two, higher voltage taps above normal operating voltage, where formerly it has been the custom to place all taps below normal.

The additional investment which compounding entails was considered more desirable to meet requirements than a similar investment in feeder copper with its doubtful result of voltage uniformity at the trolley. The periods of high peak, 730 volts at no-load, for which the interphase transformer is solely responsible, were of such short duration that these were not detected at the feeder outlet of the station, doubtless due to a voltage reduction to normal immediately as a small load develops, at the instant of automatic closing the rectifier d-c. main line contactor.

TELEPHONE SYSTEM INTERFERENCE

Tests were conducted for inductive interference on the various communicating circuits that parallel the trolley line for several miles in both directions from the substation. Perfect satisfaction was expressed by the telephone company engineers on the freedom from noise developed and it was surprising to note there was less interference with rectifier in operation than the noise experienced from operation of the motor-generator sets in the adjoining manual station.

This was accomplished by connecting between station bus and rail ground a filter system tuned to resonance at the characteristically pronounced frequencies developed by the rectifier equipment. This filter comprises four networks, each consisting of an air reactor and condenser. Under a test with the resonant shunt on the circuit, the harmonic voltages were reduced to approximately one-fifth the value without the shunt. These frequencies are rated at 300-600-900-1200 cycles.

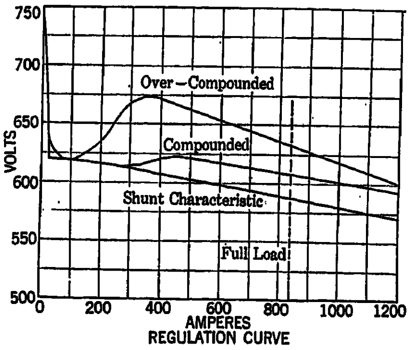


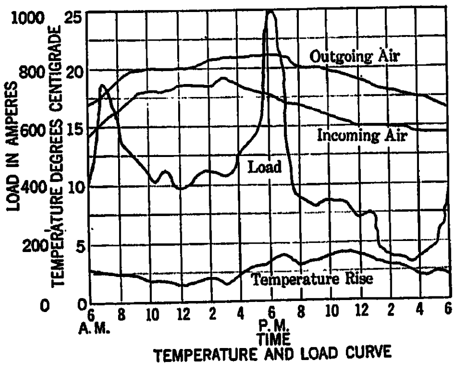
FIG. 6

VENTILATION

The Inglewood Station is provided with forced air for transformer cooling and general station ventilation. Cool air enters above roof line through the two belfrey towers, down separate shafts, to filters located at rear of each transformer unit; thence from transformer room through louvres to machine room, from which it is discharged by one motor-operated exhaust blower, located near roof. The blower operates continuously, except as controlled by under-speed relays, or whenever both units are shut down. The 11,000 cu. ft. per min. give a complete change of air in the building at the rate of ten times per hour. During periods of hottest summer days, at 40 per cent load factor, the maximum temperature rise of transformer oil by thermometer is 27 deg. cent.; while general room temperature averages 3 deg. cent. rise above outside temperature. At other enclosed 1000-kw. substation using converters, a temperature rise of 7 deg. cent. is the general average. Radiation of heat from rectifier tank, heaters, and accessories, is calculated at 25 per cent of total kilowatt loss equivalent, and does not raise the room temperature over 1 deg. cent. following maximum load periods. Fig. 7 shows air temperatures with 24-hr. load curve.

WATER COOLING SYSTEM

Tap city water is used, averaging 20 deg. cent. with discharge of waste water into cesspool. The fixed charges on investment covering a closed circulating system or any other method of cooling and circulating water were found to be unreasonable compared to the annual cost of wasting water as used in this case. A water meter installed on each rectifier intake line gives means of checking the rate of flow for various temperatures. The total 24-hr. water consumption equals 825 cu. ft., giving a rate of 0.9 gal. per min. per 100 amperes, which is considerably higher than the manufacturer's estimate, but could be reduced without fear of over heating.



TEMPERATURE AND LOAD CURVE

FIG. 7

The cooling water for the mercury condensation pump flows continuously and has been adjusted by hand valve to a rate of 1/5 gal. per min., to obtain slightly under 30 deg. cent. temperature on discharge. A water jacket of considerable volume surrounds the vacuum chamber of the rectifier. It is fundamentally necessary to keep the temperature of the jacket within certain limits, because the mercury vapor pressure is controlled more by this water temperature than by anything else. The flow of tank cooling water is regulated by an automatic thermostat operated valve. It is set to open at a value of 33-35 deg. cent. and to close at 30-32 deg. cent. During the period that the temperature of the outgoing water is lower than 30 deg. cent. the operating valve is closed automatically; which is the case when the tank is under extremely light load, or is shut down.

The jacket heaters are adjusted to come on automatically, to maintain the water above 25 deg. cent. temperature. A check for a three day period on the frequency of the jacket heaters to come on with an idle unit, showed an average per 24 hr. of 5 times on, at an average of 6 min. per interval.

The heat developed at the anode tip is carried upward to the anode radiators through the efficient action of mercury cooling and condensing near the top of the anode chamber. It is vital to the performance that a certain fairly high temperature be maintained on the anodes to prevent mercury condensing on the tips. Under ordinary load with this station, the anode heaters are not in use, being frequently on and off during the extremely light load periods under 150 amperes.

VACUUM CONTROL OPERATION

High vacuum is of prime importance in the operation of the rectifier. Satisfactory operation depends upon the maintenance and checking of the degree of vacuum. Under normal conditions, the rectifier operates at approximately 0.1 of a micron—being 0.0001 millimeter of mercury pressure (absolute) or 1/7,600,000 of an atmosphere. In order to obtain this very low pressure a pumping system is used, involving a roughing pump or oil pump, and a fine pump or mercury condensation pump, the two operating in series. The rough pump is a motor-driven mechanical pump operating under oil, and will obtain a pressure by itself of 5-40 microns. In order to obtain the finest degree of vacuum to 0.1 micron or less, the mercury condensation pump is operated in series with the roughing pump, which will obtain a theoretically perfect vacuum and pump against a back pressure of 3000-4000 microns. An electric heater delivers heat to a boiler holding about 70 cu. cm. of mercury, which sends a stream of mercury vapor up through the condensation pump, through a pipe toward the incoming side of the pump. This action of boiling, condensing, and returning to the boiler of the mercury is a ceaseless cycle, so that the gases are constantly being brought down with the vapor and then forced out of the pump into a line to a receiving tank located between the condensation pump and the oil rotary pump. The rough pump draws the gas away from the receiving tank and forces it into the atmosphere. There is just enough heat applied to the mercury in the mercury pump so that all is condensed and returned within the pump itself. The pipe line which leads from the rectifier to the mercury pump is surrounded by water, and any mercury which enters this pipe never reaches the mercury pump, but is condensed and falls back into the rectifier chamber. After the high vacuum has been obtained the automatic vacuum protection shuts the oil rotary pump down, and this degree of vacuum is maintained for long periods requiring the operation of the pump at intervals of one or two hours a day only to a possible one hour in several days. The mercury condensation pump is kept in operation at all times and pumps into the receiving tank what gases develop and what seepage there is in the rectifier.

The automatic control features contain a few special and interesting means of protection. Several devices have been included with the vacuum system for suitable protection in case of vacuum failure. In addition, they function to control the starting and stopping of the oil rotary pump. A thermocouple vacuum gage, a millivolt meter, and a mercury contacting device perform the following operations:

1. Start oil rotary pump, if vacuum falls to 2.5 microns.
2. Lock the station out, if vacuum falls to 15 microns.
3. If station has been locked out and vacuum of 1 micron is again obtained, the oil rotary pump stops after a time delay, and the station is allowed to go back on the line.
4. If the oil rotary pump has started, due to vacuum falling to 2.5 microns, when the vacuum returns to one micron the pump is shut down after a time delay.

With a rectifier, reverse current can occur only at the instant of the arc back or a short circuit of the electrode. If this occurs, a high-speed breaker, connected for such reversed direction of current, will trip-out, disconnecting the unit from load and reclose within a few seconds. Three consecutive openings of this breaker locks out the unit. There have been no arc backs with the Inglewood Substation rectifiers.

There are conditions in operation which develop a high-voltage kick and which might do injury to a transformer windings. Protection against this possibility is obtained through absorption by connecting a group of condensers with resistors across one leg of each wye of the power transformer low-tension windings and with the interphase transformer; also, as added protection through short circuiting, a pellet type of arrester parallels each of these groups.

The arc drop is influenced by the state of the vacuum. The exciting arc is established the instant of closing the circuit and is maintained during the entire load period. The ½-kw. exciter generator has a load of 7 amperes at 65 volts.

TABLE IV
COMPARISON OF DOUBLE-UNIT CONVERTER AND RECTIFIER AUTOMATIC DEVICES

Device	Converter	Rectifier
Main current parts	15	7
Protective relays	29	28
Auxiliary devices	36	45
Total	80	80

The number of control devices, switches, etc., required for the complete two-unit rectifier, has been compared, as given by Table IV, with those required for a synchronous-converter installation.

For the rectifier there are one-half the number of main current carrying parts, practically the same number of protection features, with a slightly greater number of auxiliary devices, totaling an equal number for both types of units.

INSPECTION AND MAINTENANCE

Regardless of an equal number of control devices and switches, as given by Table IV, which consists of a few special pieces of apparatus and devices of delicate construction, the frequency or general routine inspection for this substation has been conservatively established on an interval of every two weeks. A daily visit of one hour is made to take necessary meter readings, check general state of small rotating equipment, and force the operation of the vacuum pump against its automatic control, so as to assure a faster rate of seasoning-in of the vacuum tank. This practise is not absolutely necessary, but it is our method of giving this new type of equipment all the attention deserved. This inspection rate is considered ample and commensurate with the service various parts are called upon to render. The automatic converter substations of this company require weekly inspection and a two hour daily visit, which includes some cleaning up. This rate for converter is necessary, regardless of the importance and assurance from long familiarity with equipment and control principles.

Aside from cleaning, adjusting, and testing regular parts of the equipment, it is found that the time and attention given to the vacuum pump, vacuum relay and water regulator, are no more of a special nature than required by the brush-raising device and master controller of the converter substations.

Every six months, and taking two men six hours, it is planned to clean the mercury in the anode heating chamber and replace all gaskets. This does not break the vacuum in the tank.

Doubt has been expressed only too often, that maintenance cost of rectifier and its auxiliaries, especially that cost incidental to the vacuum pump, would not be less than the items required to cover actual labor and cost of material for repairs to synchronous converter and its coordinated equipment. In fact, overhauling of the rectifier has been heralded as taking longer than necessary work on the synchronous converter. These doubts and claims have not come from operating engineers using the rectifier equipment.

The vacuum pump and its appurtenances are rigidly and sturdily constructed and should give less trouble than the small time-aged motor-generator set used for exciter purposes. All the necessary and essential spare parts for the rectifier cost less than the average carried for six converter stations of this company. Since these rectifiers had proper care at the initial drying-out period and have developed no sign of trouble during operation, the most that may be expected in the way of maintenance attention would be that following a two year period of operation, at which time the total expense of labor and material for overhauling all anodes, tank, vacuum seals, vacuum pump, and necessary time to dry out, should be far less than the usual attention to converters in grinding commutators, attention to new brush fit, changing oil and checking bearing alinement, together with the occasional reinsulating of windings.

Considering that there are no intermediate starting or running a-c. contactors, brush raising devices, no checking of polarity and synchronizing requirements, no massive moving parts and oiled bearings subject to excessive strains of frequent starting, with no carbon and copper dust developing to be scattered throughout the station with high velocity of circulating air, it is obvious there should be no surprise at the present claim and at the eventual proof of considerably lower cost for inspection, cleaning, and maintenance of rectifier equipment.

SAVINGS

As originally planned, the Inglewood Substation was to have two 500-kw. converter sets. The change to rectifiers was made on the consideration of various economies as enumerated. Table V has been prepared showing estimated savings in building cost, energy loss, and labor for inspection, in comparison with the synchronous converter.

The net savings in favor of the rectifier amounting to $660.00 will cover the excess cost and fixed charges of the rectifier in approximately six years, after which it is estimated the total annual saving of $2500.00 will carry 6 per cent interest charges on 50 per cent of the entire investment.

TABLE V
ESTIMATED SAVINGS

Excess cost of rectifier equipment over converter as per contract	$7,450.00	
Annual fixed charges at 12 per cent		$894.00
Excess cost of converter installation for foundadations, air ducts, air equipment, sound proofing, etc	3,540.00	
Annual fixed charges at 12 per cent		425.00
Difference in costs	3,910.00	469.00
Estimated yearly labor savings for rectifier	604.00	
Estimated yearly power savings for rectifier	525.00	
Total estimated savings for rectifier		1,129.00
Total net annual savings for rectifier		660.00

CONCLUSION

To sum it all up, what could be more simple in effecting such a method of conversion of power than to have, at the instant of load demand, a moment to check proper a-c. conditions, state of vacuum, temperature of tank and anodes, to be followed by closing of the oil switch, striking the arc and closing of d-c. line contactor—all automatically accomplished in a time elapse of 6 sec.? The average converter gets under load in 40 sec.

I trust this paper presents sufficient information of a practical nature on the Los Angeles Railway installation, to serve as a guide to those hesitating as to the choice of this type of equipment.

Discussion

C. E. Baker: Fig. 5 of Mr. Turley's paper on the Automatic Mercury-Arc Power Rectifier shows the power factor of the rectifier as measured by the usual power-factor indicator at the primary of the rectifier transformer. The paper suggests that the power factor of the rectifier may be a serious disadvantage in some installations.

In the case of rotating apparatus, the power factor is largely due to phase displacement of the fundamental wave, and the power producer is very much interested in the power factor of the connected apparatus, as it materially affects the amount of equipment required to deliver a given amount of power.

The primary current wave produced by the rectifier is somewhat distorted from the sine wave, due to the fact that the rectifier itself draws substantially square waves of anode current. There are then several harmonics present in the primary current wave. The indicated power factor of the rectifier is really the average power factor of all the harmonics and the fundamental. Actually there is very little phase displacement of the fundamental, but there may be considerable phase displacement of some of the harmonics. Therefore, the average power factor may be relatively low, while the power factor of the fundamental is practically unity.

Unless there is a complete understanding of the difference between rectified and rotating apparatus in this respect, a direct comparison between the power factor of the two classes of apparatus may be misleading, and is not justified.

D. W. Proebstel: In the paper there is a statement, the intent of which is to justify 10 or 15 per cent higher cost. I think it might have been well if this statement had been qualified by a comment relative to the voltage rating of the rectifier, knowing that the costs for increased capacity do not increase very rapidly with increased voltage rating. For instance, we have two of these rectifiers in operation at Portland, Oregon, with a rating of 750-kw. each at 1400 volts where the costs were considerably lower than a similar capacity in synchronous converters would have been.

There is one other statement in the paper that I should like to criticize. It is the one on telephone-system interference, namely, "Under a test with the resonant shunt on the circuit, the harmonic voltages were reduced to approximately one-fifth the value without the shunt. These frequencies are rated at 300-600-900-1200 cycles." I think this should have been qualified by the statement that such apparatus produces even harmonics such as the sixth, twelfth, eighteenth, and twenty-fourth harmonics.

Again referring to our pieces of apparatus which operate at 60 cycles, the frequencies of harmonics are 360, 720, 1080, and 1440. The telephone people in Portland were not slow in reminding us of the fact that these pieces of apparatus were giving them interference. An analysis was made of these harmonics, after which the General Electric Company equipped the pieces of apparatus with resonant shunts for the lower harmonics, which have very satisfactorily mitigated the telephone interference.

Chester Lichtenberg: Automatic mercury-arc power rectifier substations are relatively new for American street railway service. Mr. Turley's paper presents the results of operating experience in Los Angeles. It enables one to form a comparison between automatic stations containing mercury-arc power rectifiers and automatic stations containing the conventional synchronous converters.

Mr. Turley's paper may be considered as the second of a series. Mr. Antoniono's paper presented at Chicago in 1927 gave experience with mercury-arc power rectifiers in automatic stations on an interurban railway carrying important traffic. Mr. Turley's paper gives operating experience with similar equipment carrying important loads in urban territory.

One interesting feature of the comparison is the number of devices required by synchronous-converter and rectifier automatic stations. The number of main current-carrying parts is more than twice as great in the converter stations as in the rectifier stations. The number of protective devices is approximately the same. The number of auxiliary devices, however, is 25 per cent greater in the rectifier station than in the converter station. This condition, while it obtains at the present time, is sure to change as the operation of mercury-arc power rectifiers becomes more familiar. The synchronous-converter equipment has now been reduced to almost the fewest number of parts for successful railway service. The rectifier equipment is in the process of development. Each year witnesses modifications in the design which reduce the number of parts. It is safe to predict, therefore, that when the rectifier equipments will have been in production as long as the converter equipments have now been in service, the number of parts required for a rectifier automatic station will be reduced probably by 25 per cent.

The inspection and maintenance data given by Mr. Turley are of great importance since he has had experience not only with synchronous converters and motor generators in manually operated stations, but he has also had wide experience with synchronous converters in automatic stations.

Likewise, the estimated savings for the operation of an automatic station using mercury-arc power rectifiers are based on broad experience. Consequently, it should be of intense interest to all executives responsible for the operation of 600-volt railway systems.

G. E. Nott: At the time the Inglewood installation was ready for service, certain tests were conducted to determine the effect of the new installation upon telephone service. These tests were conducted cooperatively by the Los Angeles Railway and the local telephone company. The results were very satisfactory.

As mentioned in the paper, exposures between the railway lines and the telephone circuits throughout the territory served by both utilities are rather extensive. The exposures which were used for the tests and which were relatively close to the new substation, were somewhat less extensive, but they were considered to be fairly indicative of conditions as they existed.

As an indication of the effect obtained through the use of resonant shunts, a comparison of the voltage telephone interference factors, as measured at the d-c. bus, may perhaps be of interest. In this instance, it appeared that the addition of the shunts reduced the telephone interference factors to approximately 13 per cent of the value which obtained without the shunts. It was also demonstrated from similar measurements that the use of the shunts resulted in a voltage telephone interference factor equal to approximately 60 per cent of that which was produced by the existing rotating equipment. The latter equipment had, however, been in use over a considerable period of years and the telephone interference factor was somewhat higher than that generally obtained from similar equipment of more recent manufacture.

It is gratifying to note that the results of the tests which were conducted, indicated that, through the use of a small amount of properly designed auxiliary equipment, such as is employed at Inglewood, serious interference with telephone circuits can be avoided under normal conditions. It also appears that, from the interference standpoint, such an installation may be compared favorably to rotating equipment of modern design.

M. D. Wade: Several references have been made to telephone interferences, and I should like to hear something in the final discussion about radio interference.

L. J. Turley: There seems to be no trouble with radio reception from the rectifier installation that we have at Inglewood; in fact, I doubt very much if there could be.

With reference to the question that was raised on the 10 to 15 per cent higher cost, I appreciate the fact that my study did not go into the higher voltage of 1500 volts. Therefore I was not versed in what the relative cost would be between that and the 600-volt price, but I do realize that the higher voltage leads into a lower cost, in comparison with similar equipment of the synchronous converters.

Movements of Overhead Line Conductors
During Short Circuits

BY Wm. S. PETERSON[1] AND H. J. McCRACKEN, Jr.[1]
Associate, A. I. E. E. Associate, A. I. E. E.

Synopsis.—When overhead lines carry large short-circuit currents, the resulting magnetic forces on the conductors are such as to cause the cables to be repelled to greater distances than the usual spacings. The elementary principles involved are stated. A single-phase short circuit is shown to be the one producing the greatest movements. A theoretical calculation of the forces and actual experience showed the necessity of making tests to study the problem. A description of the tests indicates how photographic records of the movements of relatively large cables were obtained. The results of over 330 tests are shown by pictures and curves. The effects of a variation in each of the five principal variables, cable size, span length, spacing, tension, and current are discussed. A mathematical expression is derived by means of which the maximum movement of conductors in a horizontal plane can be approximately determined. It has been found possible to set up a miniature test with small wire that very closely duplicates to a small scale the movements of a larger conductor. The results indicate that it is necessary for moderately large systems to take account of these short-circuit forces in the design of their overhead systems. There is a large field for research on this subject and more work should be done.

OBJECT

THE object of this paper is to present the results of investigations recently made on overhead line conductors in order to determine the movements of those conductors when they are carrying the heavy short-circuit currents that exist in large electric distributing systems. It will give the essential data from over 330 tests that were made by the Los Angeles Bureau of Power and Light, on full sized conductors, at various spacings, spans, and tensions that might be used in practise.

REASONS FOR THE INVESTIGATION

Just as the growth of electric systems has brought the circuit breaker problem, so has it brought the problem of conductor movements. In past years power systems have been relatively small and the short-circuit currents were not large enough to seriously disturb overhead lines, so very little attention has been given to this problem.

The first case of trouble on the lines of the Los Angeles Bureau of Power and Light that gave proof that overhead line movements are such as to cause serious trouble, was on a 33-kv. line leaving the receiving station where the 110-kv. lines from the Aqueduct power plants terminate. The 33-kv. line is of 3/0 copper cable, on approximately 4.5 ft. spacing. The span lengths are approximately 400 ft. near the station, as the line is carried on some lower crossarms mounted on the same towers as the transmission line. These spans are longer than what would normally be used on a 33-kv. pole line. When a short circuit occurred about one-half mile from the station, the cables in some of the longer spans, between the point of trouble and the station, wrapped around each other so as to remain tangled. Obviously, such movements were due to magnetic forces set up by the large short-circuit currents. The same action has been suspected in distribution primaries, when spans have been burned in two.

If we grant the possibility of such a range of movement, it can be shown that certain so called faulty relay actions, that sometimes happen, might be the result of conductors touching each other and relaying out a section of line that should have stayed in. This would be especially true where a single line loops through several stations, and several line sections carry the same short-circuit current. Another example would be where one line interferes with an adjacent circuit.

In striving to give high class service, a power system then has the economic problem, of which is the best way to build so that trouble from conductor swinging will be avoided. To determine whether the answer is longer crossarms, more poles, heavier conductors, limitation of currents by reactors, limitation of system size, or underground distribution, is a tremendously important problem, especially to systems supplying power to rapidly growing metropolitan areas, such as that represented by Los Angeles. In order to design not only the lines, but the entire system to supply satisfactorily the future load of this city, it was essential that this problem be studied rather completely and that the engineering be based on precise and accurate data.

Investigation of engineering literature revealed that very little work, if any, had been done on this subject. The study of magnetic forces on busbars and disconnect switches apparently constitutes the nearest approach to the problem at hand. Preliminary mathematical studies of the problem indicated that the solutions were so involved that it would be necessary to make tests on full sized conductors in order to have exact data to apply to the economic design of lines.

ELEMENTARY STATEMENT OF THE PROBLEM AND FUNDAMENTAL THEORY

Although the subject is new in its application to overhead lines, the fundamental principle is an old and familiar one; namely, that two wires carrying currents in opposite directions are repelled from each other. The more convenient conception is the one where a conductor has a force exerted on it, due to its carrying a current in the magnetic field set up by the other conductor. The fundamental formula expressing the force of repulsion between two long straight conductors is as follows:[2]

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[1] Both of the Bureau of Power and Light of the City of Los Angeles, California.

A. I. E. E. Initial Prize Paper.

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$$F' = 2.04\, i_1\, i_2\, (L/D)\, 10^{-8} \qquad (1)$$

where F' is the instantaneous force in kilograms, i_1 and i_2 are the instantaneous values of current flowing in the conductors in amperes, L is the length of the conductors in any units, and D is the distance between the conductors in the same units. If currents varying as a sine wave are assumed, then the instantaneous values of force vary as a sine wave of double frequency, similar to that for instantaneous power in a-c. circuits. For given currents, the maximum value of force is greatest when the two currents are in phase or 180 deg. out of phase, the latter being the condition that exists in a single-phase short circuit.

Since a conductor has an appreciable mass, its movement is more influenced by the average of these impulses than by their instantaneous values. It can be shown that the average value of force, in lb. per ft. of conductor, is given, for a single-phase circuit, by the following formula:[3]

$$F = \frac{0.045\, I^2}{10^6\, D} \qquad (2)$$

where I is the effective value of current in each of the conductors, D is the distance between conductors in feet, and F is the force per ft.

It is interesting to note that for 15,000 amperes, and a separation of 4 ft., the force is approximately 2.5 lb. per ft.

In the case of three-phase short circuits, we find that each wire is acted upon by a force due to its own current and the resultant field set up by the currents in the other two wires. In general, the conductors tend to move away from each other and the forces are smaller than for the same effective values with single-phase current. In the case of a flat arrangement of the three conductors, the forces are such on a balanced three-phase short circuit, as to cause the two outward conductors to move outward, while the center conductor tries to move back and forth at double the circuit frequency, which means that it practically stands still. The worst condition for this arrangement of conductors, is for a single-phase short circuit to occur between the center and one of the outer conductors, thus causing these conductors to be violently repelled from each other. Since the single-phase consideration is the one leading to the most unfavorable condition, the remainder of the discussion will be limited to that particular phase of the problem.

Reference to Fig. 1 will help in the explanation of the mechanics involved in the motion of the conductors. It is a cross-section of two horizontally spaced conductors, taken at the center of the span. The initial position of the conductors is shown by the small circles. At some interval of time after the start of the short circuit, the conductors will have reached some position indicated by the solid lines. At any such instant, it is seen that the conductor is acted upon by three forces; first, the constant force, W, which represents the weight of the conductor; second, the force F, due to the current, which is in this case a horizontal force and becomes less as the conductors move further apart; and third, the force T_R, due to the tension in the cable, and which may be assumed radial. The unbalanced resultant force accelerates and stretches the conductor, thus increasing T_R. The velocity of the conductor carries it beyond the point of static equilibrium of the three forces until it is stopped by the tension developed. It then snaps back until stopped by the repulsion due to the current, and starts outward again. The problem is complicated by the fact that the high current heats up the conductor, adding to its length and decreasing the tension, and also by the fact that each portion of the cable in half a span length is a different distance from the other cable and has a different value of magnetic force, so the cable is no longer strictly following a catenary curve.

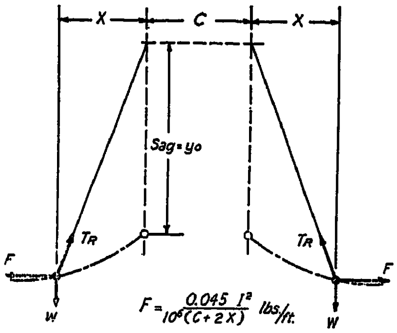

Fig. 1—Cross-Section Showing Forces Acting on Horizontally Spaced Conductors

For any given type of spacing we find that the problem contains six independent variables, namely: wire size, span length, sag (or tension), spacing, current, and the length of time the current is flowing. The resulting mathematical complexity of the problem made advisable full scale tests to determine the laws of action.

Description of Tests

The large number of variables made a complete experimental determination of values impossible. Therefore a set of standard conditions was established and then each variable was investigated with respect to this standard point. Excepting for a few special tests, the variable, time, expressing duration of current, was eliminated by leaving the current on long enough for the cable to reach the end of its first throw. The standard condition was 3/0 cable, 150 ft. span, 12,000 lb. per sq. in. tension, 4 ft. spacing and the highest value of current obtainable from the equipment available for the test. In addition to the single variable variation with respect to the above point, it was planned to obtain a few scattered points representing other possible combinations of the variables.

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[2] See "Standard Handbook for Electrical Engineers," (1922) Sect. 2, par. 41.

[3] See Appendix A

The cable sizes tested were No. 2, 3/0, 500,000 cir. mils, and 4/0 weather-proof. The spans used were 150, 300, 450, and 600 ft. The stringing tensions used were 12,000, 18,000, and 24,000 lb. per sq. in., approximately. The spacings were 2, 4, 8, and 12 ft. Currents varied from 4000 to about 13,000 amperes.

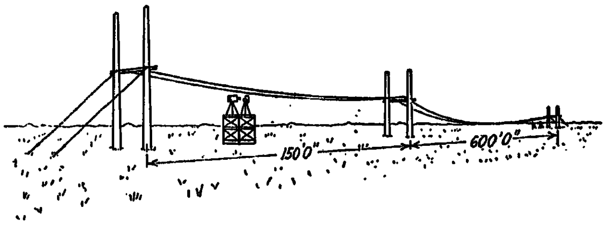

Fig. 2—General Arrangement of Test Spans and Cameras

In making the tests two spans were set up and the movements of each were measured simultaneously to save time. Fig. 2 gives a general idea of the arrangement of the spans. Two dead-end H-frame structures were set up 750 ft. apart. At an intermediate point was placed another similar structure. By moving this latter pair of poles, the span lengths were varied. The cable was dead-ended through suspension type insulators and clamped to pin type insulators at the intermediate poles. At one end of the line the two cables were connected through an oil switch to the low-voltage side of the transformers supplying power for the test. The far ends were short circuited. To obtain the highest currents a jumper was placed across the cables at the end of the first span.

The record of the movement of the wire was made photographically. In order to do this, an automobile headlight bulb was fastened by means of an insulated clamp to the cables at the center of each span. The power for the light was supplied through flexible leads from a storage battery. In addition, some reference lights, a fixed distance apart and mounted truly horizontal were used. The cameras used to record the movements of the lights were mounted as nearly as possible on a horizontal line from the lights so no corrections for angularity would have to be made in scaling distances from the pictures. In order to have a record of the time for the cable to reach any point a disk with one or two holes in it was revolved in front of the lens by means of a synchronous motor. Thus a dotted line record of the movements of the wire was obtained.

By running the tests after 1:00 a. m. a considerable portion of the power generating capacity of the Los Angeles Bureau of Power and Light system could be used. The night work also facilitated the photography. The wiring diagram, Fig. 3, shows the equipment and connections used for the test. The portion labeled 33-kv. bus represents two wires of a three-phase 33-kv. line, to which was connected the single-phase bank of eight 1000-kv-a., 33,000/2400 volt transformers which furnished the power for the test loop. The low-voltage circuit of this bank is shown as a full line diagram to indicate the details more completely. By means of the disconnect switches in this circuit, the number of transformers could be varied and therefore a variation in current could be obtained. The circuit was closed through the solenoid operated oil circuit breaker in the 2400-volt circuit and opened by a relay operating the 33-kv. breaker. An oscillograph element was connected to a shunt in the secondary circuit of a 3000/5 ampere current transformer.

In addition to the main circuit, it was necessary to have auxiliary circuits for supplying power to the oscillograph, synchronous motors, lights on the cables, etc. A telephone circuit was used to correlate properly the work of the men operating the cameras, oscillograph, and oil circuit breakers.

Results of Tests

Horizontal Spacing. In presenting the results, only a few of the many pictures that were taken can be shown. These will be grouped so as to have three or more together, so comparisons can be made as the variations are pointed out. Tables I and II give data pertaining to the various pictures that will be shown. Complete data obtained from all the tests are given in Appendix B.

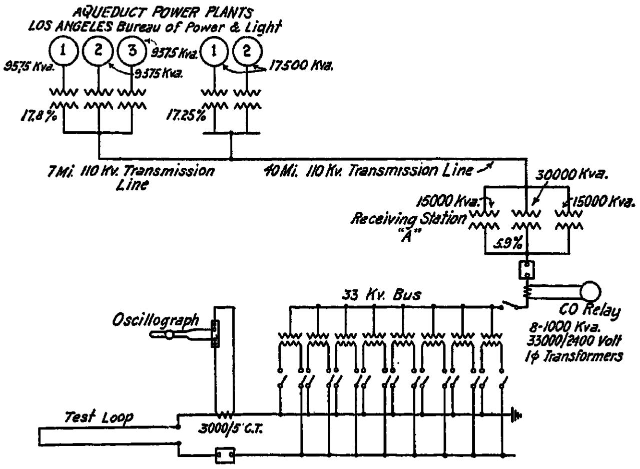

Fig. 3—Wiring Diagram for Test

Fig. 4 shows the movements of a 3/0 copper cable on a 600-ft. span for three different tests. These pictures show the variation in the deflection for different values of current. The distance between the large dots where the cable started from is 4 ft. (1.22 m.), so there is an indication that the cable moved 12.8 ft. (3.91 m.) from its initial position with a current of only 7430 amperes. The time to reach the point of maximum deflection in

TABLE I
RESULTS OF TESTS
CONDUCTOR MOVEMENTS WITH CABLES HORIZONTALLY SPACED

Fig. no.	Test no.	Cable Size	Span ft.	Tension, lb. per sq. in.	Sag ft.	Spacing ft.	Current		Maximum deflection data			
							Amperes	Duration sec.	Radius ft.	Horiz. throw-ft.	Vert. movement-ft.	Time sec.
4	1B	3/0	600	12,800	13.5	4	5,470	1.21	16.8	8.65	−0.91	1.21
"	2B	"	"	"	"	"	6,150	1.01	17.9	10.8	−0.84	1.19
"	5B	"	"	12,300	14.1	"	7,430	1 +	19.4	12.8	−0.51	1.16
7	2A	3/0	150	12,800	0.85	4	6,550	1.01	1.51	1.24	0	
"	3A	"	"	"	"	"	7,100	0.52	1.65	1.41	0	0.33
"	7A	"	"	12,300	0.88	"	8,340	0.87	2.08	1.87	0	0.34
"	8A	"	"	"	"	"	11,420	0.75	3.04	2.91	0	0.33
"	10A	"	"	"	"	"	13,500	0.69	3.63	3.52	0	0.31
11	3A	3/0	150	12,800	0.85	4	7,100	0.52	1.65	1.41	0	0.33
"	133A	"	300	14,000	3.1	"	7,200	0.95	5.56	4.50	−0.16	0.60
"	133B	"	450	12,800	7.6	"	7,030	0.95	11.00	7.67	−0.29	0.86
"	5B	"	600	12,300	14.1	"	7,430	1 +	19.4	12.8	−0.51	1.16
13	13B	3/0	600	24,000	7.2	4	7,030	0.99	11.5	8.14	−0.7	0.88
"	11B	"	"	18,000	9.6	"	7,140	0.92	15.2	11.0	−0.91	1.04
"	5B	"	"	12,300	14.1	"	7,430	1 +	19.4	12.8	−0.51	1.16
24	70A	4/0W	150	16,900	0.8	1.5	13,300	1.05	3.90	3.82	0	0.26
"	71A	"	"	13,500	1.0	"	13,400	1.03	3.98	3.86	0	0.26
"	72A	"	"	10,400	1.3	"	13,320	1.05	4.24	4.07	0.16	0.27
"	76A	"	"	5,900	2.3	"	13,450	1.07	5.62	5.38	0.65	0.31

Amperes given is average current during time it takes for cable to reach maximum deflection.
4/0*W* designates 4/0 weather-proof cable, weighing 0.8 lb. per ft.

Fig. 4 is approximately 1.2 sec. The current was interrupted very close to the point of maximum deflection. This gives the worst condition for the tangling of the cables on the return movement. In the lower picture, the cable acquired a velocity of 18 ft. (5.49 m.) per sec. near the center of its travel. At the end of the throw, the sag distance was increased to 19.4 ft. (5.91 m.), or nearly 6 ft. (1.83 m.) greater than the initial sag of 13.5 ft. (4.12 m.).

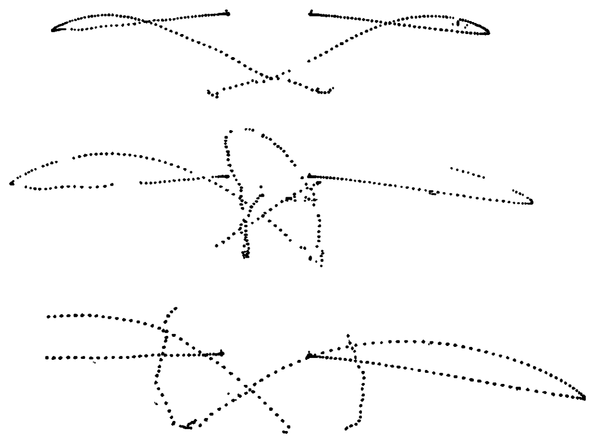

FIG. 4—COMPARISON OF CONDUCTOR MOVEMENTS FOR DIFFERENT CURRENTS WITH 3/0 CABLE, 4 FT. HORIZONTAL SPACING, 600 FT. SPAN, 12,800 LB. PER SQ. IN. TENSION, 13.5 FT. SAG

Top, 5470 amperes; middle, 6150 amperes; bottom, 7430 amperes

Approximately the same general characteristics of movement were observed for spans of 450 and 300 ft., excepting that the maximum deflection and the time to reach that point were reduced.

The results that were obtained with 3/0 cable on a 150-ft. span are indicated in Fig. 7. This length of span is quite typical of the spans that are used in city line construction. The time required for the cable to reach the maximum deflection is very short for this group, being of the order of ¼ to ⅓ of a sec. The current remained on from ½ to 1 sec.

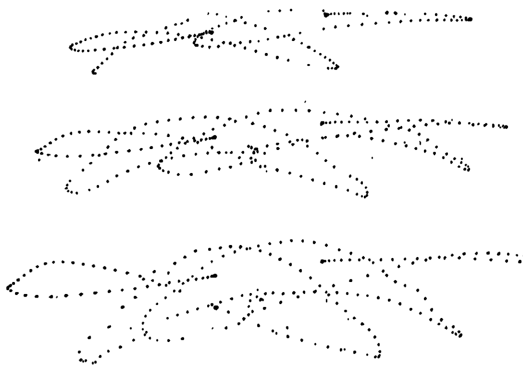

FIG. 5—COMPARISON OF CONDUCTOR MOVEMENTS FOR DIFFERENT CURRENTS WITH 3/0 CABLE, 4 FT. HORIZONTAL SPACING, 450 FT. SPAN, 12,800 LB. PER SQ. IN. TENSION, 7.6 FT. SAG

Top, 5400 amperes; middle, 6410 amperes; bottom, 7030 amperes

In the top picture, it can be observed that the cable was thrown out twice by the current. The camera shutter was closed about the same time that the current went off, so none of the subsequent oscillations of the cable towards the center are shown.

In the next picture underneath is shown the condition where the current went off real quickly, and while the cable was on its way back. This resulted in the elliptical paths shown. In the next picture, the cable had started on its second trip out, when the current went off, thus producing a smaller oscillation. If the current could be interrupted at precisely the right point, considerable of the oscillation, wherein the cables approach each other, could be avoided. In the next two pictures, this was accomplished, but not premeditatedly.

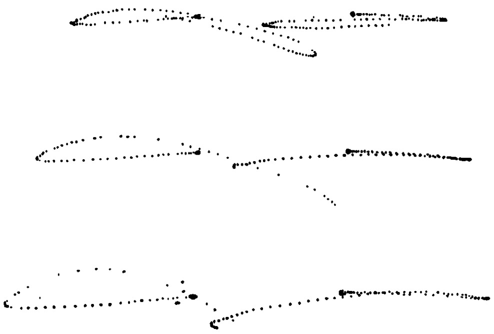

Fig. 6—Comparison of Conductor Movements for Different Currents with 3/0 Cable, 4 Ft. Horizontal Spacing, 300 Ft. Span, 14,000 Lb. per Sq. In. Tension, 3.1 Ft. Sag

Top, 5450 amperes; middle, 6500 amperes; bottom, 7200 amperes

In this short span, it can be observed that the initial movements are horizontal. The maximum outward throw in the lower picture is over 3.5 ft. (1.07 m.). The maximum velocity reached is approximately 20 ft. (6.1 m.) per sec.

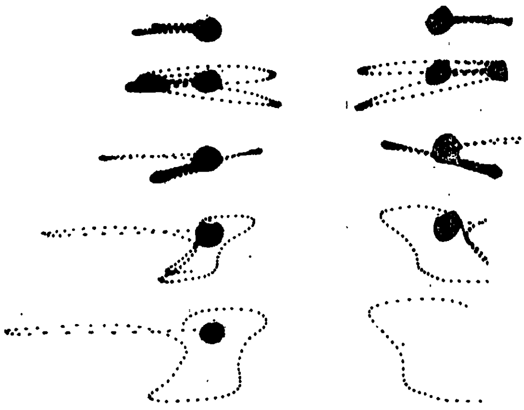

Fig. 7—Comparison of Conductor Movements for Different Currents with 3/0 Cable, 4 Ft. Horizontal Spacing, 150 Ft. Span Approximately 12,800 Lb. per Sq. In. Tension, 0.85 Ft. Sag

Top, 6550 amperes; 2nd, 7100 amperes; 3rd, 8340 amperes; 4th, 11,420 amperes; bottom, 13,500 amperes

Due to the fact that in the great majority of cases the movement of the conductors was so nearly horizontal, it was possible to develop a formula by which could be calculated approximately the maximum deflection and the sag of the conductors at this point. The results of such calculations and the points obtained by test are shown in Fig. 9. Here is shown the variation of maximum deflection with current. The data obtained from Fig. 4 and Fig. 7 are plotted together with that from other tests.

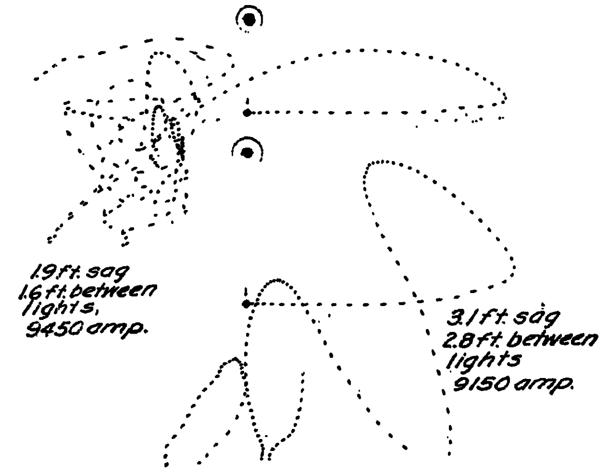

Fig. 8—Conductor Movements as Obtained in a Preliminary Test on 3/0 Cable, 4 Ft. Horizontal Spacing, 160 Ft. Span

Reference light is 0.3 ft. below line of sight between conductor supports

It will be observed that the calculated curve fits the points quite closely except that it falls a little short on the 600-ft. span curve. The extension of the results by means of the curves, derived from a purely theoretical basis and fitting the data as closely as they do, gives one confidence in their use in extrapolating to high current values. From the curves it is observed that the cables can move to unbelievable distances under the influence of 15,000 to 17,000 amperes. The derivation of the formulas will be taken up later.

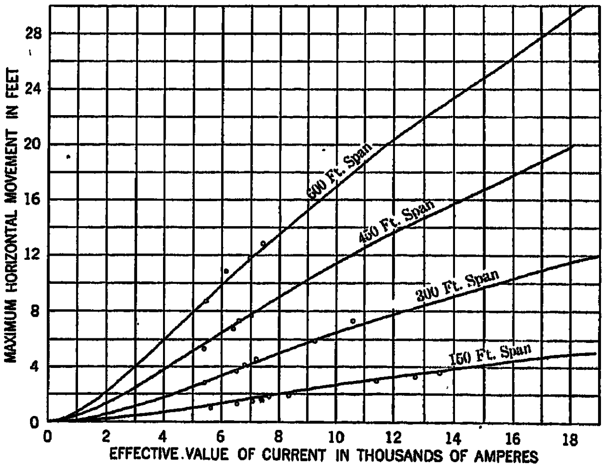

Fig. 9—Relation Between Maximum Horizontal Movement of Conductors and Current for Various Spans

3/0 copper cable, 4 ft. horizontal spacing, approximately 12,500 lb. per sq. in. tension
0—Test points—calculated curve

From the way these curves lie with respect to each other, it is possible to judge the effect of span length. A better comparison is given in Fig. 11, which shows the movements of a 3/0 copper cable, on 4 ft. spacing, with 12,000 lb. per sq. in. tension, and a current of approximately 7000 amperes, while the span is varied from 150 to 600 ft. The same data are shown by the curve for 7000 amperes shown in Fig. 12. The upper curve shows the movements that take place when the current is 15,000 amperes. The variation in horizontal movement, for a given current, spacing, and tension, is approximately as the square root of the span length cubed, that is span to the 3/2 power.

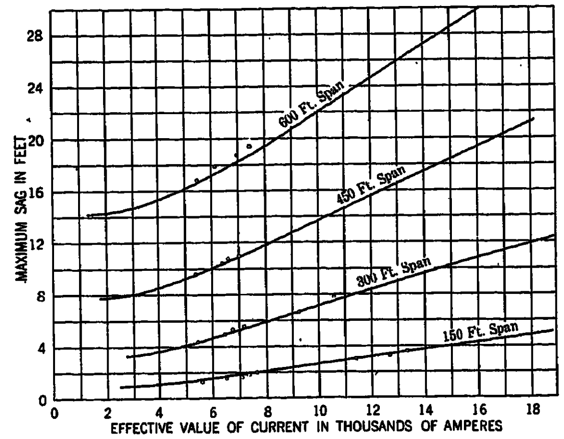

FIG. 10—RELATION BETWEEN MAXIMUM RADIAL SAG OF CONDUCTORS AND CURRENT FOR VARIOUS SPANS

3/0 copper cable, 4 ft. horizontal spacing, approximately 12,500 lb. per sq. in. tension
0—Test points—calculated curve

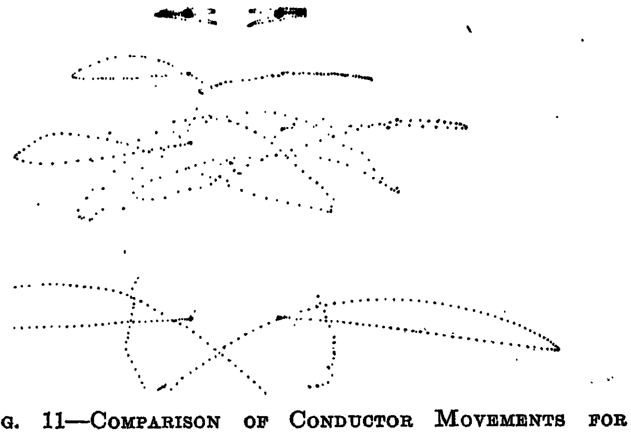

FIG. 11—COMPARISON OF CONDUCTOR MOVEMENTS FOR DIFFERENT SPANS, WITH 3/0 CABLE, 4 FT. HORIZONTAL SPACING, APPROXIMATELY 12,800 LB. PER SQ. IN. TENSION, APPROXIMATELY 7000 AMPERES

Top 150 ft. span, 0.85 ft. sag; 2nd, 300 ft. span, 3.1 ft. sag; 3rd, 450 ft. span, 7.6 ft. sag; bottom 600 ft. span, 14.1 ft. sag

It is to be noted that the time required to reach the maximum deflection varies very closely as the span length for a given tension. It has been observed that for the horizontal spacings and currents used in all the tests considered here, the time to reach the maximum throw point can be roughly determined by the formula:

$$t = \frac{\sqrt{\text{Sag}}}{3} \tag{3}$$

where the sag is expressed in feet. A more accurate empirical formula that takes care of the variation in the period of copper cable due to wire size, current, and spacing is as follows:

$$t = 0.25 \sqrt{y_o} + \frac{2.65}{\left(\frac{I^2}{A\ C}\right)^{2/3}} \tag{3.1}$$

where y_0 is the initial sag in feet; I is the effective current in amperes; C is the spacing of the conductors in feet; and A is the area of the conductor in circular mils. This formula is also for horizontal spacing and gives results with not over five per cent error.

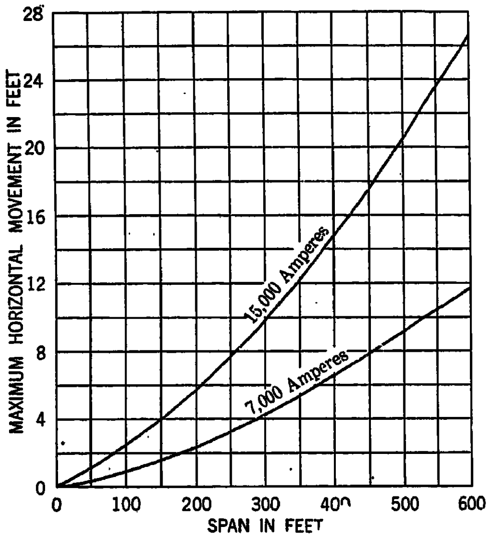

FIG. 12—RELATION BETWEEN MAXIMUM HORIZONTAL MOVEMENT OF CONDUCTORS AND SPAN FOR TWO DIFFERENT CURRENT VALUES

3/0 copper cable, 4 ft. horizontal spacing, approximately 12,500 lb. per sq. in. tension

In order to reduce the large deflections noted in the foregoing curves the use of higher tensions suggests itself. Fig. 13 shows the effect of varying tension on a 600-ft. span. See Table I for data. In this figure, doubling the tension has decreased the movement from nearly 13 ft. (3.96 m.) to a little over 8 ft. The tendency for the path of the conductor to rise rather than droop is typical of low tensions.

The variation in movement as the tension is changed is shown to better advantage in Fig. 15, where the test values for various span lengths are plotted. These curves indicate that the movement is varying approximately inversely as the square root of the tension. The movement is therefore not cut down as rapidly as the sag, which is varying inversely as the tension. Very high values of tension cannot be used because of other loadings imposed on the cable by wind and ice in addition to that produced by the magnetic forces.

The effect of spacing is shown in curve form in Fig. 18. The curves are drawn for a current of 7000 amperes. Although it can be observed that spacing reduces the movement of the individual conductor, there is not a great change in the total space occupied by the swinging conductors. The great difference between the curve for the 150 ft. span and the others indicates the importance of using short spans.

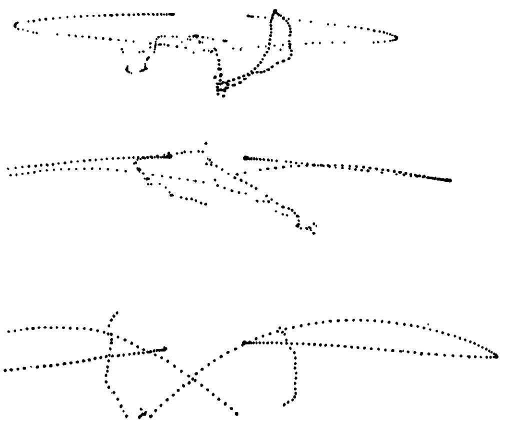

Fig. 13—Comparison of Conductor Movements for Different Tensions, with 3/0 Cable, 4 Ft. Horizontal Spacing, 600 Ft. Span, and Approximately 7000 Amperes

Top, 24,000 lb. per sq. in., 7.2 ft. sag; middle, 18,000 lb. per sq. in., 9.6 ft. sag; bottom, 12,300 lb. per sq. in., 14.1 ft. sag

Fig. 22 indicates how the use of heavy conductors will decrease the movements. Fig. 24 is also an example of a heavy conductor, but is also interesting because it is representative of conditions on a feeder circuit. It is a picture of 4/0 triple braid weather-proof cable, on a 150 ft. span, with a spacing of 1.5 ft. The current in each case was approximately 13,300 amperes. The variation in the movements as the tension is changed are shown. It can be observed that with the highest tension, which is larger than what would normally be used, the movement is approximately 4 ft. (1.22 m.) or 2.5 times the spacing. This condition is readily obtainable within a short distance of a distributing station on a large system.

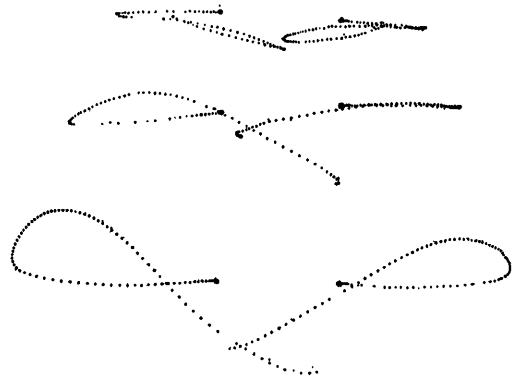

Fig. 14—Comparison of Conductor Movements for Different Tensions, with 3/0 Cable, 4 Ft. Horizontal Spacing, 300 Ft. Span and Approximately 7000 Amperes

Top, 20,600 lb. per sq. in., 2.1 ft. sag; middle, 14,000 lb. per sq. in., 3.1 ft. sag; bottom, 6370 lb. per sq. in., 6.8 ft. sag

Fig. 25 will serve to show the variation in movement with current for the tensions shown in the previous figure.

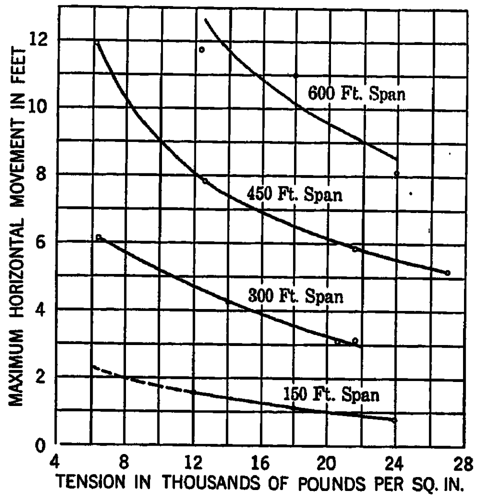

Fig. 15—Relation Between Maximum Horizontal Movement of Conductors and Tension for Various Spans

3/0 copper cable, 4 ft. horizontal spacing, approximately 7000 amperes

In Fig. 27 an effort has been made to consolidate on one sheet a considerable amount of information on the performance of one particular conductor at a given spacing and a given tension. It shows the location of the maximum point of throw both vertically and horizontally for any current and span length.

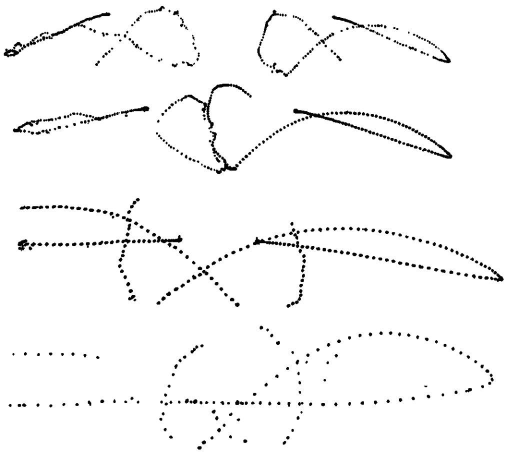

Fig. 16—Comparison of Conductor Movements for Different Spacings, with 3/0 Cable, Horizontal Spacing, 600 Ft. Span, Approximately 12,500 Lb. per Sq. In. Tension and Approximately 7000 Amperes

Top, 12 ft. spacing; 2nd, 8 ft. spacing; 3rd, 4 ft. spacing; bottom, 2 ft. spacing

The origin of coordinates at the upper left hand corner is on the line of sight between supports of the conductor. The distance down indicates the sag below that point at the center of the span. Distances to the right indicate the extent of movements from the initial position. For example, the initial sag for a 300 ft. span is indicated on the vertical axis a distance of 3.3 ft. down, corresponding to the assumed tension of 12,800 lb. per sq. in. This is the position of the cable for zero current. For various currents the cable will be propelled to the right. For a current of 5000 amperes the cable reaches the point shown by the intersection of the 300-ft. span line and the 5000-ampere line. The location of the point shows both its vertical and horizontal position with respect to the center about which it swings. The curves are drawn from combined test and calculated data with intermediate values approximated. Due to the test data available, the tensions used are not precisely alike throughout the whole range of values.

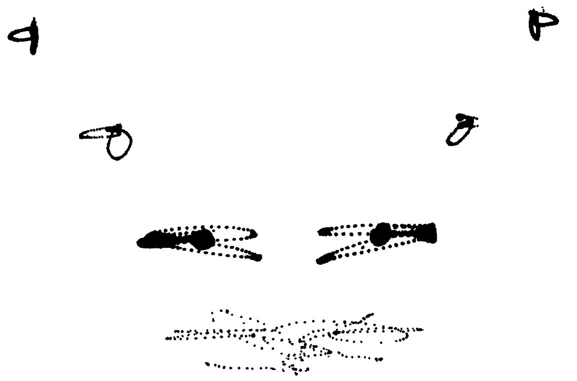

Fig. 17—Comparison of Conductor Movements for Different Spacings, with 3/0 Cable, Horizontal Spacing, 150 Ft. Span, Approximately 12,500 Lb. per Sq. In. Tension and Approximately 7000 Amperes

Top, 12 ft. spacing; 2nd, 8 ft. spacing; 3rd, 4 ft. spacing; bottom, 2 ft. spacing

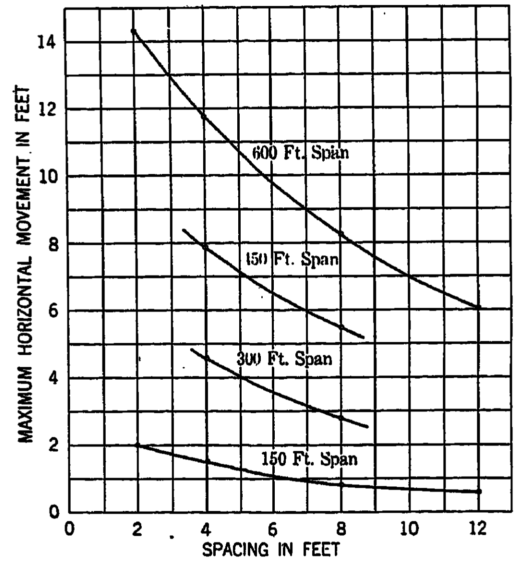

Fig. 18—Relation Between Maximum Horizontal Movement of Conductors and Spacing for Various Spans

3/0 copper cable, approximately 12,300 lb. per sq. in. tension and 7000 amperes

Results with Vertical Spacing. In making tests on cables arranged above one another, it is found that the movements are primarily vertical, which leads to a confusion of dots, so that only the maximum points can be determined. The results are therefore best presented by means of curves. Only a limited investigation was made with respect to vertical construction, so only a few miscellaneous results will be shown. Referring to Fig. 29, the initial position of the conductors with no current flowing is indicated on the vertical axis a distance of 2 ft. from the center line midway between the conductors. This represents a spacing of 4 ft. For different values of short-circuit current, the maximum movement of the conductors on the first throw is indicated by the curve. The upper group of curves applies to the upper conductor and the lower group to the lower conductor. The movements of the upper and lower cables are not necessarily alike. It is interesting to note that the movement of the upper cable, up to current values of 7000 amperes, does not change much for various span lengths. For higher currents, tests were made only on the 150- and 300-ft. spans. The 300-ft. span has a movement of the upper conductor that seems to be almost erratic and makes a large change in movement for a small change in current.

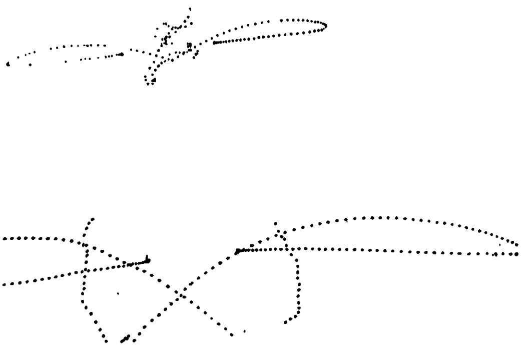

Fig. 19—Comparison of Conductor Movements for Different Conductor Sizes, with 4 Ft. Horizontal Spacing; 600 Ft. Span; 12,300 Lb. per Sq. In. Tension, 14.1 Ft. Sag and Approximately 7000 Amperes

Top, 500,000 cir. mils; bottom, 3/0

In Fig. 30, a study is made of this extreme movement of the 300-ft. span. A picture was taken with just a slight offset from the vertical so the dots would not confuse each other. A plot of the movements of the two conductors was made with respect to time. One pair of curves shows the movements for 5600 amperes and the other pair shows the movements for 10,800 amperes. It is to be noted that as the current increases, the time to reach the maximum point increases for the upper conductor, and decreases for the lower conductor. For the high current values, the lower conductor reaches its maximum sooner than the upper one, and as the tension of the conductor pulls it upward, the increasing magnetic force due to the decreasing distance between the cables, causes the upper conductor to have an increased upward acceleration after it had begun to lose velocity. There is probably some critical value of current at which this phenomenon occurs.

Tests on the 450 and 600 ft. spans with 3/0 cable have indicated that the movement of the bottom conductor is greater than that of the upper. Apparently, on long spans, the heating effects alone are such as to cause the conductors to sag great distances, thus dropping both conductors to a lower point, and possibly decreasing the upward throw of the top conductor and adding to the downward throw of the lower conductor.

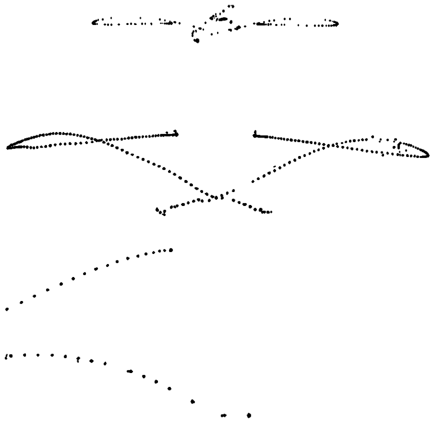

Fig. 20—Comparison of Conductor Movements for Different Conductor Sizes, with 4½ Ft. Horizontal Spacing, 600 Ft. Span, 12,300 Lb. per Sq. In. Tension, 14.1 Ft. Sag

Top, 500,000 cir. mils, 5870 amperes; middle, 3/0 cable, 5470 amperes; bottom, No. 2 wire, 4810 amperes

Fig. 31 shows a few miscellaneous results with 500,000-cir. mil cable in the vertical arrangement.

In general the movements for vertical construction are less than for horizontal, except at the higher current values.

Results with Triangular Spacing. Pictures were also taken of two cables as they might be arranged as part of three cables constituting a triangular arrangement. Fig. 33 is a picture of the movements of a 3/0 copper cable, on a 300 ft. span with 4 ft. spacing, at a 30 deg. angle with the vertical. The four pictures are for four different current values. Table II gives the data pertaining to this figure.

The same effect, wherein the upper wire takes a long flight at the higher current values, is to be observed in this arrangement, just as was the case for vertically spaced cables. The maximum throw in the lower right hand picture is a little over 11 ft. for the upper conductor.

In order to make a comparison for different angles or amounts of offset, Fig. 34 has been prepared. The current is approximately 10,500 amperes in each case. The tensions are very similar. As the cables approach horizontal spacing, the throw of the upper wire decreases and that of the lower increases.

No tabulation of movements is made for these particular tests as it is difficult to decide what part of the motion is of greatest interest. The great bulk of information for such arrangements probably must be obtained from direct tests.

MATHEMATICAL CONSIDERATIONS

Most of the mathematical analysis that the authors have done on this problem has been with reference to horizontal spacing. This is slightly more favorable to work with than the other cases due to the symmetry of the movements. Efforts were made to calculate the path of the cables. An equation was found that was of the correct form, but it would be very difficult to determine the various coefficients in terms of the physical dimensions. This effort was abandoned.

It became evident, however, that the principal thing of interest in connection with horizontal spacing was the location of the maximum deflection point. As in most cases the cables move out approximately horizontally and reverse direction at this point, the horizontal component of velocity at such a time is zero, and in most cases the vertical component of velocity is negligibly small. On this basis, all the mechanical energy imparted to the cable by the magnetic forces during its motion has been absorbed by the stretching of the cable.[4] The input energy is the integral or summation of the instantaneous force times the distance through which it acts. From the equation for the magnetic force at any point, this input energy can be determined. This is equated to the energy stored up in the cable by stretching it. Allowance must be made for the increase

TABLE II
CONDUCTOR MOVEMENTS WITH CABLES TRIANGULARLY SPACED
(See pictures for actual movements)

Fig. no.	Test no.	Cable size	Span ft.	Tension lb. per sq. in.	Sag ft.	Spacing ft.	Amperes	Duration of current sec.	Offset ft.
33	179A	3/0	300	10,300	4.2	4	5570	0.96	2.0
"	181A	"	"	"	"	"	7040	0.98	"
"	183A	"	"	"	"	"	9120	0.87	"
"	184A	"	"	"	"	"	10500	0.73	"
34	177A	3/0	300	11,400	3.8	4	10800	0.69	1.0
"	184A	"	"	10,300	4.2	"	10500	0.73	2.0
"	190A	"	"	13,100	3.3	"	10350	0.77	3.0

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[4] See Appendix C.

in temperature of the cable due to the high currents. With this method of procedure, and one slight empirical correction, the following formula is derived, for copper cable:

$$\frac{0.0447\, y_0 \dfrac{I^2}{A} \log_e \dfrac{C + 1.5\, X_m}{C}}{K_0\, (R_m^2 - y_0^2)} = \frac{18 \times 10^6\, K_0}{T_1^2}\left(\frac{R_m^2 - y_0^2}{y_0}\right) + 2 - 5.13 \times 10^6\, \frac{I^2 t}{A^2\, T_1} \qquad (4)$$

where A, is the area of the conductor in circular mils; C, is the initial distance between the cables in feet; I, is the effective value of the current in amperes in each cable (single phase); K_0 is the ratio of total weight per foot of cable plus any weather-proof or other covering it might have, to the weight of the bare cable; t, is the time in seconds required to reach the maximum deflection, and can usually be taken as $\sqrt{y_0}/3$; T_1, is the initial stringing tension in pounds per square inch; y_0, is the initial sag at the center of the span, in feet; R_m, is the maximum radial sag at the point of maximum throw; and X_m, is the maximum horizontal movement in feet. The formula applies to copper cable, with a modulus of elasticity of 14,000,000, and of 97.3 per cent conductivity.

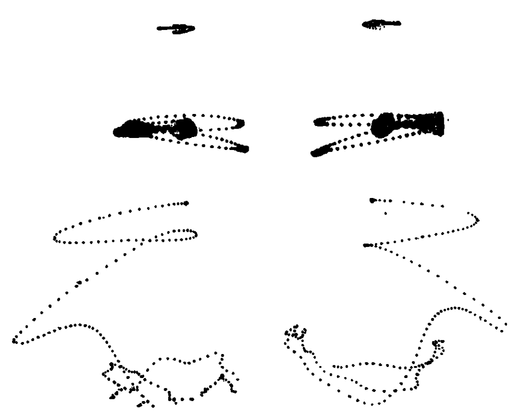

FIG. 21—COMPARISON OF CONDUCTOR MOVEMENTS FOR DIFFERENT CONDUCTOR SIZES, WITH 4 FT. HORIZONTAL SPACING, 150 FT. SPAN, APPROXIMATELY 12,800 LB. PER SQ. IN. TENSION, 0.85 FT. SAG

Top, 500,000 cir. mils, 7300 amperes; middle, 3/0 cable, 7100 amperes; bottom, No. 2 wire, 6020 amperes

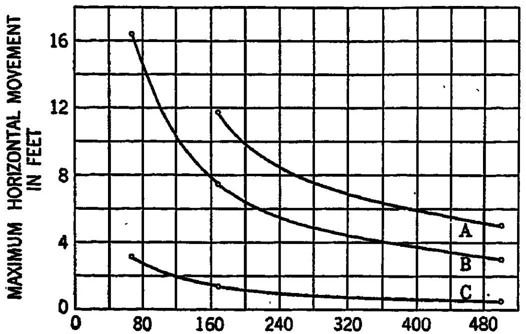

FIG. 22—RELATION BETWEEN MAXIMUM HORIZONTAL MOVEMENT OF CONDUCTORS AND WIRE SIZE

Four ft. horizontal spacing, approximately 12,500 lb. per sq. in. tension A—7000 amperes, 600 ft. span. B—4800 amperes, 600 ft.span. C—7000 amperes, 150 ft. span

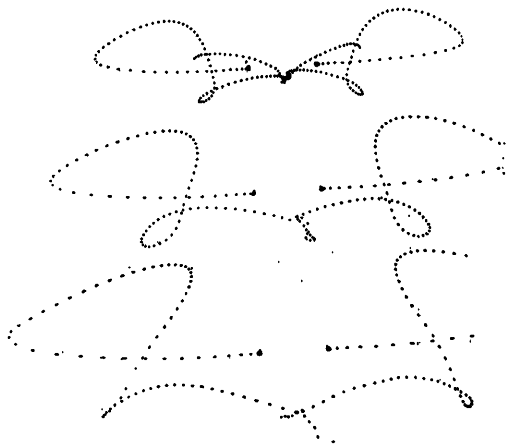

FIG. 23—COMPARISON OF CONDUCTOR MOVEMENTS FOR DIFFERENT CURRENTS WITH 4/0 WEATHER-PROOF CABLE, 1.5 FT. HORIZONTAL SPACING, 150 FT. SPAN, 5900 LB. PER SQ. IN. TENSION, 2.3 FT. SAG

Top, 8150 amperes; middle, 10,890 amperes; bottom 13,450 amperes

This formula is deficient in one respect, namely, that both R_m and X_m are unknown, so there is an infinite number of combinations that would satisfy the equation. However, it was observed that most of the tests showed the movement to be nearly horizontal. This establishes a relation between R_m and X_m that makes it possible to eliminate R_m and obtain the equation in the following form:

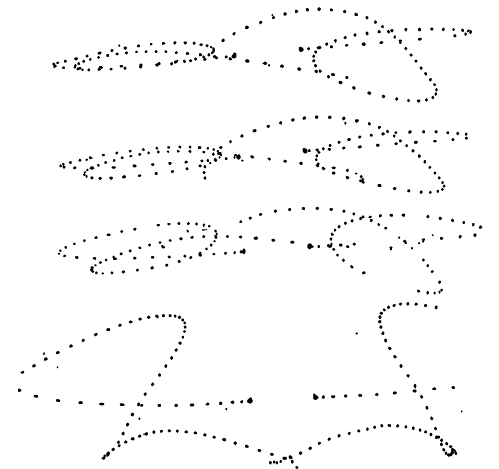

FIG. 24—COMPARISON OF CONDUCTOR MOVEMENTS FOR DIFFERENT TENSIONS WITH 4/0 WEATHER-PROOF CABLE, 1.5 FT. HORIZONTAL SPACING, 150 FT. SPAN, APPROXIMATELY 13,300 AMPERES

Top, 16,900 lb. per sq. in., 0.8 ft. sag; 2nd, 13,500 lb. per sq. in., 1.0 ft. sag; 3rd, 10,400 lb. per sq. in., 1.3 ft. sag; bottom, 5900 lb. per sq. in., 2.3 ft. sag

$$\frac{0.0447\, y_0 \dfrac{I^2}{A} \log_e \dfrac{C + 1.5\, X_m}{C}}{K_0\, X_m^2} = \frac{18 \times 10^6\, K_0\, X_m^2}{T_1^2\, y_0} + 2 - 5.13 \times 10^6\, \frac{I^2\, t}{A^2\, T_1} \qquad (5)$$

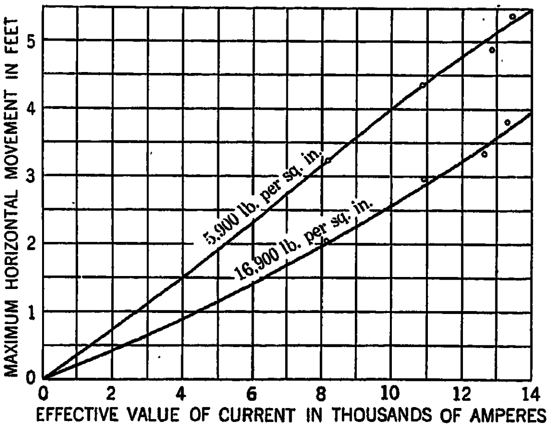

Fig. 25—Relation Between Maximum Horizontal Movement of Conductors and Current for 4/0 Weather-Proof Triple Braid Cable with 1.5 Ft. Spacing and 150 Ft. Span at Two Different Tensions

This equation, due to its logarithmic form, has to be solved for X_m by trial. It is this equation that was used to make the calculated curves shown in Fig. 9. This equation will not give exact values for all cases, but in general it gives a conservative answer, that is, larger values of movement rather than smaller. For large spacings, and for small wire sizes, that is, where the magnetic forces are relatively small and where the heating effects are relatively large, the conductors move on a drooping path. This means that the cable becomes stretched to a certain value of radial sag with a smaller value of horizontal movement. Consequently, such cables will not move as far horizontally as indicated by the equation. If the tensions are low, the cables have a tendency to rise rather than droop. In this case the vertical component of velocity remains a considerable amount as the point of maximum deflection is reached. As some percentage of the input energy is stored in velocity instead of elongation of the cable, the formula again gives a deflection that is large, as it assumes all the energy caused elongation.

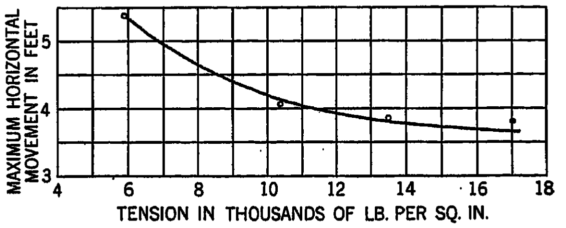

Fig. 26—Relation Between Maximum Horizontal Movement of Conductors and Tension for 4/0 Weather-Proof Triple Braid Cable with 1.5 Ft. Spacing, 150 Ft. Span, and Approximately 13,300 Amperes

In making calculations for very large current values, it was found necessary to use a more exact expression for taking care of temperature effects. In order to do this the last term of the equation, which term is:

$$5.13 \times 10^6\, \frac{I^2\, t}{A^2\, T_1}$$

is replaced by:

$$\frac{63{,}400}{T_1}\left(e^{\frac{74.5\, I^2\, t}{A^2}} - 1\right)$$

See Appendix C for more complete development.

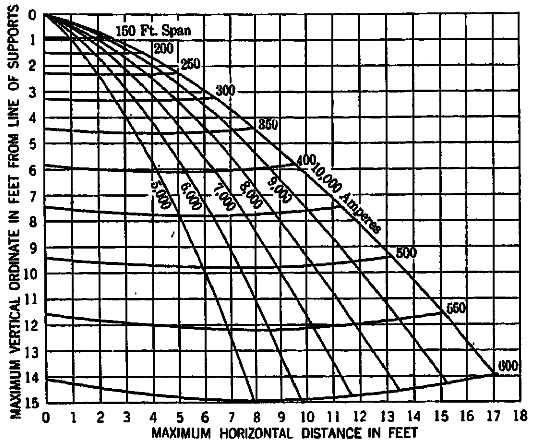

Fig. 27—Coordinates of Point of Maximum Deflection for Various Currents and Spans for 3/0 Copper Cable, 4 Ft. Horizontal Spacing and Approximately 12,800 Lb. per Sq. In. Tension

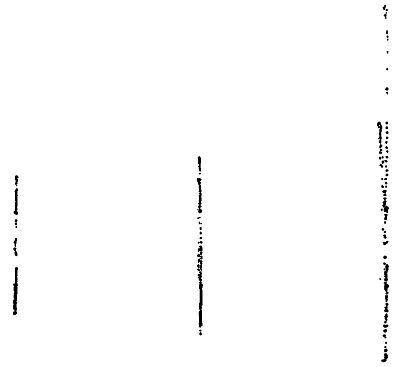

Fig. 28—Comparison of Conductor Movements for Different Currents with 3/0 Cable, 4 Ft. Vertical Spacing, 300 Ft. Span, 12,400 Lb. per Sq. In. Tension, 3.5 Ft. Sag

Left, 5550 amperes; center, 6990 amperes; right, 10,620 amperes

As yet no entirely satisfactory formula has been developed for calculating the movements of vertical conductors.

Miniature Tests. On the basis of these formulas it is possible to determine the proper dimensions of a miniature test to reproduce the same conditions to a smaller scale. This should make possible the solution of any problems of the type discussed here, by making a small scale set up and taking an actual test, which can be performed probably as quickly as any calculations could be made. The miniature test to use is the one that will have each term of the equations mentioned above equal in value to the same term for the larger size being duplicated. To do this assume some scale multiplier *n*; that is, some number by which the small scale distances will be multiplied to equal the large test. It can then be shown[5] that circular mils, spacing, sag, movement, and current all have the multiplier *n*. Unit tension and time have a multiplier $n^{1/2}$ and the multiplier for span length is $n^{3/4}$. Point-to-point calculations of conductors with vertical spacing have indicated that the same multipliers apply to vertical arrangements.

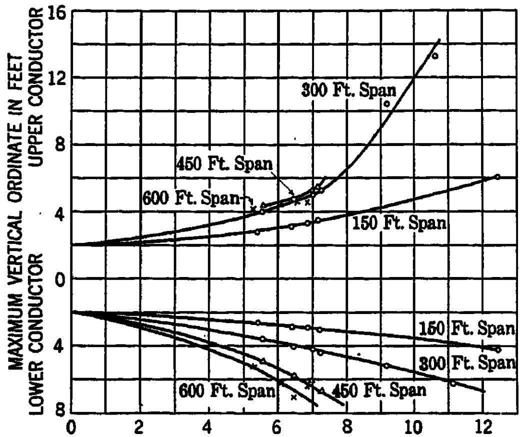

Fig. 29—Relation Between Maximum Vertical Movement of Conductors and Current for Various Spans

3/0 copper cable, 4 ft. vertical spacing, approximately 12,000 lb. per sq. in. tension

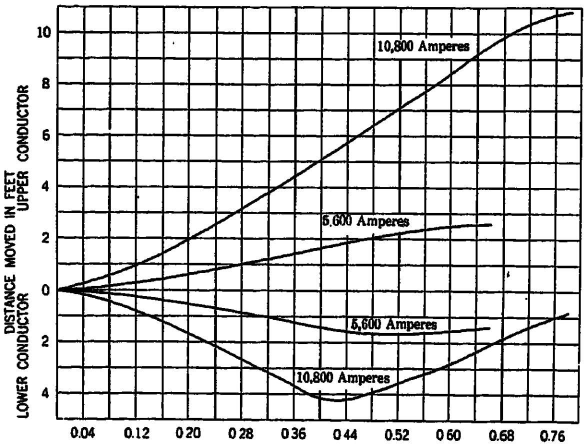

Fig. 30—Relation Between Movement of Conductors and Time for Two Different Currents

3/0 copper cable, 4 ft. spacing with 1 ft. offset from true vertical, 300 ft. span, 11,400 lb. per sq. in. tension and 3.8 ft. sag

Miniature tests on horizontal spacing, but with the current read by means of an ammeter instead of an oscillograph, agree with the large scale tests being duplicated, within the accuracy of the ammeter reading. More recent tests on vertical arrangement, where the current in the miniature setup was read with an oscillograph, indicated excellent agreement up to points where the currents and movements were very large. For instance, miniature tests on No. 10 wire to duplicate 3/0 cable on 4 ft. vertical spacing, with a 300 ft. span, and a tension of 12,000 lb. per sq. in., gave results correct within 6 in. up to 8500 amperes. This is as close as could be expected, as the errors introduced by the distance from the wire to the filament of a flashlight bulb used to trace the path are of the order of $\frac{3}{8}$ in., which becomes 6 in. when multiplied by the proportionality constant. For those currents and movements which could be tolerated in good line design, it is very probable that miniature tests are commercially accurate. More investigation is necessary on this subject before the values taken from miniature tests can be used with perfect assurance as to their being completely representative of the full scale condition.

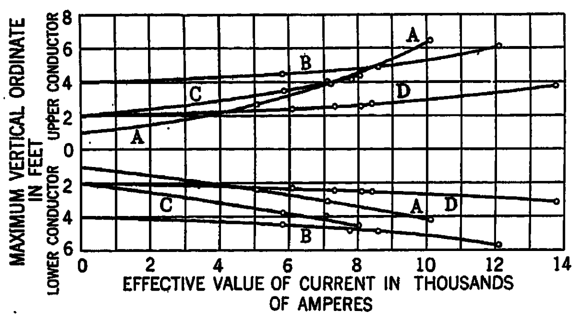

Fig. 31—Relation Between Maximum Vertical Movement of Conductors and Current

500,000 cir. mil copper cable, vertical spacing, approximately 12,500 lb. per sq. in. tension

A—300 ft span, 2 ft. spacing. B—300 ft. span, 8 ft. spacing. C—600 ft. span, 4 ft. spacing. D—150 ft. span, 4 ft. spacing

Interpretation of Results

In almost all line design, the main factor considered in determining the spacing between wires has been voltage. Only to a small extent has span length been considered as affecting the necessary spacing. From the data in this paper it seems that an additional factor, namely, short-circuit currents and the movements which they cause, must be considered. On large systems it will apparently be necessary to correlate the choice of reactors, spacing, span length, conductor size, and tension, so as to obtain the most economical line that will not be subject to trouble due to swinging conductors.

A detailed economic design cannot be worked out in the space allotted to this paper. However, a few of of the most salient factors should be pointed out. From the data it is evident that for the most practicable span lengths and tensions, the cables reach their maximum deflection in so short a time, approximately ⅓ of a sec., that with present day designs of oil circuit breakers, it is almost impossible to interrupt the current sufficiently fast to reduce the throw of the cables. This makes it necessary to accept as the first basis of design, that the current be considered as being on until the cable reaches its maximum position. Then in order to be safe it is desirable to assume that the current goes off at the maximum position, so as to produce the most unfavorable condition during the return of the conductors, that is, when there is no current opposing their motion while swinging back.

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[5] See Appendix D.

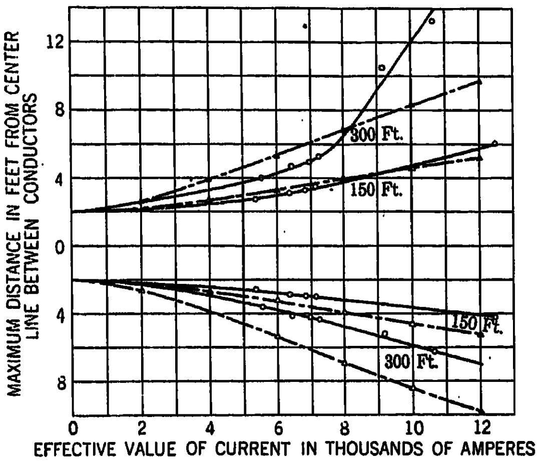

FIG. 32—COMPARISON OF MOVEMENTS OF CONDUCTORS WITH VERTICAL AND HORIZONTAL SPACING FOR VARIATION IN CURRENT

3/0 copper cable, 4 ft. spacing, approximately 12,000 lb. per sq. in. tension, spans as indicated. Solid lines are vertical spacing. Dot and dash lines are horizontal spacing

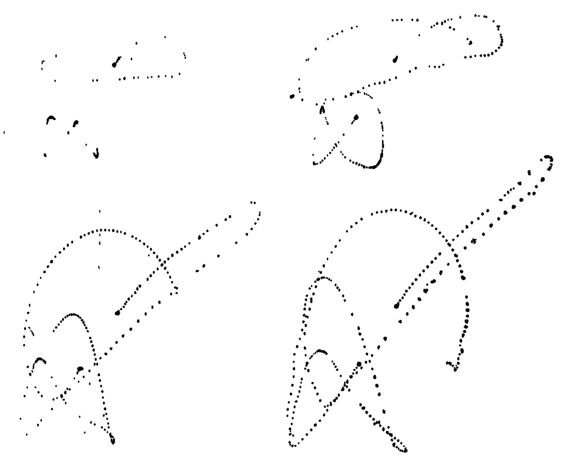

FIG. 33—COMPARISON OF CONDUCTOR MOVEMENTS FOR DIFFERENT CURRENTS WITH 3/0 CABLE, 4 FT. ANGULAR SPACING (30 DEG.), 300 FT. SPAN, 10,300 LB. PER SQ. IN. TENSION, 4.2 FT. SAG

Upper left, 5570 amperes; upper right, 7040 amperes; lower left, 9120 amperes; lower right, 10,500 amperes

It may be that for some purposes it will be sufficient if the conductors do not interfere with some other conductor or circuit on their path outward. In accepting this basis of judgment, one would be assuming that the overlapping of the conductors as they snap back would do no harm. This is a possible criterion for a short, unimportant line that is not so connected that it supplies any other lines that may have short circuits and which should be relayed off without affecting the line in question.

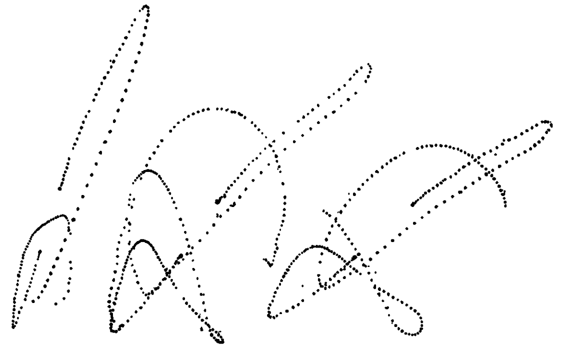

FIG. 34—COMPARISON OF CONDUCTOR MOVEMENTS FOR DIFFERENT ANGULAR SPACINGS (4 FT. WITH DIFFERENT HORIZONTAL OFFSETS), 300 FT. SPAN, APPROXIMATELY 11,000 LB. PER SQ. IN. TENSION, 4 FT. SAG, APPROXIMATELY 10,500 AMPERES

Left, 1 ft. offset, 14.5 deg.; center, 2 ft. offset, 30 deg.; right, 3 ft. offset, 48.6 deg.

A more generally useful basis is to attempt to design the line so that for the short-circuit current contemplated, the conductors will avoid meeting at the midpoint between the wires as they return. If the current is off when the cables are returning from their maximum deflection, they will in general swing back to such a point that the sag measured radially is the same as that at the maximum deflection. In general it is sufficiently accurate to assume that the conductors will swing as far towards the center as they swung outward beyond their initial position. If this assumption is made, a line would be so designed that with a short-circuit current flowing, it would not be deflected as much as half of the spacing between conductors.

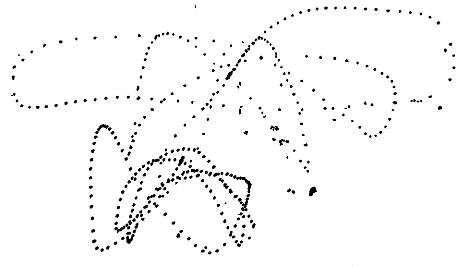

FIG. 35—MOVEMENT OF 3/0 CABLE, WITH 4 FT., 30 DEG., ANGULAR SPACING; 450 FT. SPAN, 12,500 LB. PER SQ. IN. TENSION, 7.8 FT. SAG, 7310 AMPERES

To indicate what this means, reference is made to a set of design curves shown on Fig. 37, which curves were calculated by means of Equation (5). These curves are for 3/0 conductor on horizontal spacing, with a stringing tension of 12,000 lb. per sq. in. For a given current they show the relation necessary between span and spacing to avoid having the conductor thrown outward more than one-half the spacing. Such curves can be prepared for any wire size and tension. It will be found that if the curves are prepared for various values of amperes squared divided by circular mils, they vary only slightly for different wire sizes. Referring to Fig. 37, and selecting some value of short-circuit current such as 16,000 amperes, it will be noticed that there is a choice of the use of 13 ft. spacing with a span of 245 ft.; 10 ft. spacing with a span of 195 ft.; 8 ft. spacing with a span of 160 ft.; 4 ft. spacing with a span of 90 ft.; or any other intermediate values. Which of these choices is the best to use is to be determined from a cost estimate, and any other pertinent requirements.

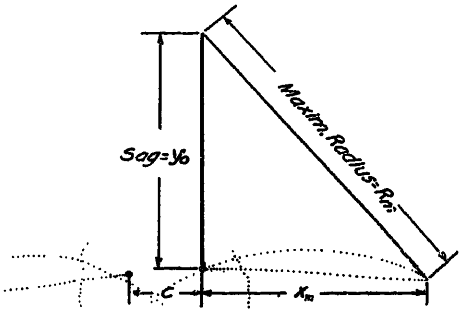

Fig. 36—Dimensional Symbols for Horizontal Spacing

This one example probably indicates that lines on systems become more expensive as the size of the system increases, requiring larger spacings, shorter spans, and heavier copper, more or less independent of the size of the load being supplied on that particular line.

Possibly one of the most satisfactory solutions of this problem will come from the use of parallel lines between stations in a network. Then in case of a short circuit on a line, it may be permissible to let that line interfere with itself, while carrying the total short-circuit current, but the lines on the remainder of the system would be so designed that they would give no interference while carrying their share of the short circuit, which would be a much smaller value of current than that in the line which is in trouble. As the magnetic forces vary as the square of the current, conditions are readily improved by designing in this way.

Short-circuit forces also enter into the choice of an economic voltage for a line. If the line itself constitutes the principal reactance that limits the short circuit, then the higher the voltage of the line, the higher the short-circuit current, and the greater the difficulty would be with conductor movements. On the other hand, if the equipment supplying the line constitutes the principal reactance, then the currents are reduced by the use of high voltages.

When this latter condition exists, the high voltage would be favorable from the standpoint of conductor movements, but it is possible that the increased cost of higher voltage oil circuit breakers, transformers, and station space might over-balance the advantages to be derived from the higher voltage.

A low voltage line may give trouble and require very short spans near the station, but as the short-circuit current in such lines is decreased very rapidly as the point of short circuit is further from the station, the spans may be lengthened as the distance from the station becomes longer. This phase of the problem also enters into the economic solution. The proper solution for the dimensions of a line is a decidedly particular one, dependent on the system characteristics and local conditions.

The one thing that seems most evident is that the spans on a large system must be small. This refers to those parts of the system where the voltage is low enough that large currents are encountered. Also, it is likely that an overhead network of too large capacity would not be economical, as the advantages due to diversity, etc., would be lost in excessive line costs. This leads to the advocation of the idea that a central station company should have its total system consist of several nearly independent, relatively small capacity networks, practically complete in themselves; but loosely coupled, that is, coupled through high reactance to each other for standby service. This reduces the short-circuit currents to moderate values, and should lead to a lower cost system.

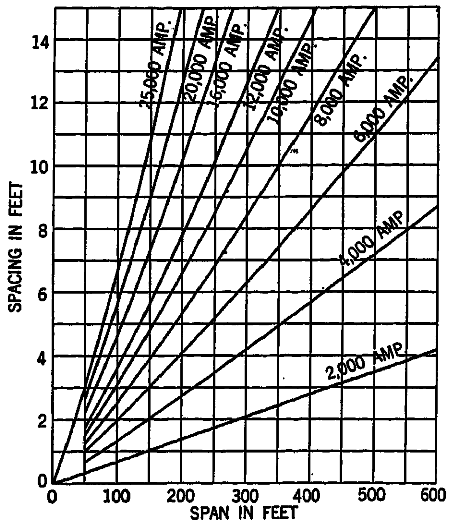

Fig. 37—Typical Design Curves for Horizontal Spacing

3/0 copper cable, 12,000 lb. per sq. in. tension.

For a given current, the curves show the relation between spacing and span when the conductors have a maximum deflection of one-half the spacing

Conclusions

In closing, the following conclusions should be drawn from the results described in the paper:

1. It is necessary to take account of short-circuit forces in designing overhead lines.
2. Present mathematical and experimental data on the movements of overhead conductors during short circuits are very incomplete. A large field exists for research on this problem.
3. It would seem that the improvements in system and line design that can come from a study of this problem would justify various central station companies in extending and making public the research on this subject.

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Appendix A

CALCULATION OF AVERAGE FORCE PER FOOT OF CONDUCTOR

Starting with Equation (1), with the definition of symbols as there given,

$$F' = 2.04\, i_1\, i_2\, (L/D)\, 10^{-8} \qquad (1)$$

If the force is expressed in pounds per foot instead of total kilograms, and if the currents are assumed to be sine waves, the following expression is obtained:

$$F'' = \frac{0.045 \times \sqrt{2} \times I_1 \sin(\omega t) \times \sqrt{2} \times I_2 \sin(\omega t + \phi)}{10^6 \times D}$$

where I_1 and I_2 are effective values of current in the two conductors, ω is the angular velocity in radians per second, t is the time in seconds, ϕ is the phase angle in radians between the currents in the two conductors, D is the distance between conductors in feet, and F'' is the force in pounds per foot of conductor. When F'' is positive the force is one of attraction. When ϕ is π or 180 deg., that is, when the currents are in opposite directions, the highest values of instantaneous force are obtained for given current values. This is the condition that is found in a single-phase circuit. For single phase, the currents in each wire are equal and opposite, so a simpler expression can be written from the above.

$$F_i = \frac{0.045 \times 2 \times I^2 \sin^2(\omega t)}{10^6 \times D}$$

where F_i is the force of repulsion between conductors in pounds per foot and I is the effective value of current in amperes.

This force varies from zero to a maximum at double the frequency of the circuit. The movements of the conductors can be assumed to be due to the average value of this force. This can be obtained by integrating the above expression for instantaneous force for the period represented by π radians and dividing by π. Let F be the average force in pounds per foot. Then:

$$F = \frac{2 \times 0.045\, I^2}{10^6 \times D} \times \frac{1}{\pi} \int_0^{\pi} \sin^2(\omega t)\, d(\omega t)$$

$$= \frac{2 \times 0.045\, I^2}{10^6 \times D} \times \frac{1}{\pi} \times \frac{\pi}{2}$$

$$F = \frac{0.045\, I^2}{10^6 \times D} \qquad (2)$$

Appendix B

ADDITIONAL DATA GIVING RESULTS OF TESTS NOT SHOWN IN MAIN PORTION OF PAPER

Fig. 5 and Fig. 6 are shown here. These figures together with Fig. 4 and Fig. 7 will serve to indicate the effects of increasing current on the four different span lengths used in the series of tests.

Fig. 8 shows two of the first three pictures that were taken of full scale tests. These tests were preliminary to the more comprehensive tests that have been discussed in the paper. In this case the reference light is 0.3 ft. below the line of sight between supports. The movement shown in the lower picture is 4.9 ft., while that in the upper is 4.3. The results shown in this figure were the immediate reason for starting on the more complete research. The tensions used in this span were lower than those used in the remainder of the tests. The difference in the pattern is due to this fact. The pertinent data are given in the figure. The current values given in this figure are not entirely reliable.

Fig. 10 presents the same results as those in Fig. 9 except that they are replotted to show the variation in radial sag at the point of maximum sideways deflection. In this curve the exceedingly great increase in sag for long spans is to be noted. However, for per cent increase in sag, the shorter spans show the greater values.

Fig. 14 is a companion figure to Fig. 13 and shows the effect of tension on a 300-ft. span.

The effects of spacing can be noted in Fig. 16 and Fig. 17. For a given current, the path of the wire becomes more drooping as the larger spacings are used, which is due to the slower horizontal movements combined with the same increased sag due to heating.

Figs. 19, 20, and 21 were prepared to give a comparison of different conductor sizes. The current in the No. 2 wire in Fig. 21 was on an excessively long time.

Fig. 23 gives a comparison of movements due to different currents. It was the best example of symmetry that was found in the entire group of tests. The effects of increased tension for 4/0 weather-proof wire are indicated in the curve designated as Fig. 26.

Fig. 28 will give an idea of the appearance of the pictures taken of conductors with vertical spacing. The extreme movement indicated in going from 7000 to over 10,000 amperes should be noted.

In Fig. 32 is given a comparison of movements for horizontal and vertical movements, plotted in the same form as has been used in presenting the vertical movements.

An additional picture of the movements that take place with angular spacing is given in Fig. 35, where the results with a 450 ft. span are shown.

The remainder of the results can be obtained from a tabulation of all tests, which will follow.

The test numbers indicate the order in which the tests were made. The designations *A* and *B* refer to short and long spans respectively. The tension given is the tension in the cable at the time of the test, which is calculated from the measured sag, using the formula given in Section II, Paragraph 103, of the 1922 Edition of the "Standard Handbook for Electrical Engineers." The current given is the average of the effective values during the time it takes the cable to reach its maximum deflection. This is, in general, different for the two spans during the same test. The column headed "Duration" gives the time for which the current was on. The "Maximum Point" is the point at which the radial sag is a maximum and in general corresponds to the point at which the horizontal movement is a maximum. These values are given in the columns headed "Radius" and "Horizontal Throw." If this point is appreciably above or below the initial position, the amount is indicated in the column marked "Vertical Movement." The time required to reach this maximum point is recorded in the column headed "Time." Discrepancies in this column are due to the difficulty in counting the dots in some pictures.

A symbol has been used to describe the type of movement taking place. The first letter describes the direction of the movement on the way out; that is, *H*, means that the conductor moved horizontally; *D* means that it drooped or sagged downward on its way out, while *R* means that it rose above the horizontal. The amount of the drooping or rising can be judged by the values given under "Vertical Movement." The second letter describes the movement on the return. The letter *S* means that the cable started back along the same path that it came out on, whether that path is drooping, horizontal, or rising. The letter *O* means that in returning it rose above the outward path and returned over or above that path. The letter *U* means that it returned under the original path. The tabulation for horizontally spaced conductors follows immediately, in Table III.

The tabulation of results for vertical tests is similar to that for horizontal spacing except that the maximum movement on the first throw is given for both the upper and lower conductors. The time it takes to reach that point is also given where the confusion of dots is not such as to interfere with counting them and thus determining the time. The tabulation follows in Table IV.

Appendix C

Calculation of Maximum Movement of Overhead Conductors with Horizontal Spacing

Calculations Based on Energy Relations

In these calculations, no attempt will be made to determine the complete path of the conductor, but merely to calculate the maximum horizontal deflection on the first throw. As was indicated in the main portion of the paper under Mathematical Considerations, it will be assumed that all of the mechanical energy imparted to the conductor will be used in stretching it to its maximum sag, for the velocity energy and the energy used in raising the cable vertically are very small at this point. It will also be assumed that the point of maximum horizontal throw is the same as the point of maximum sag.

The following symbols will be used in this development:

A = Area of cross-section of conductor in circular mils.

α = Temperature coefficient of expansion, (= 0.000,009,6 per fahr. deg. for copper).

B = Area of cross-section of conductor in square inches.

C = Spacing between conductors in feet.

E = Modulus of elasticity, (14,000,000 for copper cables).

F = Magnetic force in pounds per foot of conductor.

I = Effective single-phase short-circuit current in each of two conductors in amperes.

K_0 = Initial loading ratio, *i. e.*, ratio of weight of cable loaded with weather-proof, or other covering, to weight of bare cable.

L = Length of span in feet.

m = Weight of cable one ft. long with 1 sq. in. cross-section, in pounds (= 3.85 for copper).

q = Factor by which the horizontal deflection at center of span is multiplied to obtain a distance which, when used in input energy equation, will give average energy per foot of cable.

R = Radius or sag in feet at center of span.

R_m = Radius or sag in feet at center of span at point of maximum deflection.

r = Resistance in ohms per foot.

t = Time in seconds required to reach maximum deflection.

TABLE III

RESULTS OF TESTS, SHOWING CONDUCTOR MOVEMENTS WITH CABLES HORIZONTALLY SPACED

						Current		Maximum point data				
Test	Cable Size	Span ft.	Tension lb./in.^{2}	Sag ft.	Spacing ft	Amperes	Duration sec.	Radius ft.	Horiz. throw ft.	Vertical movement ft.	Time sec.	Type of movement
23A	3/0	150	12,500	0.87	2	7,600	0.92	2.51	2.34	0	0.30	HS
24A	"	"	"	"	"	7,450	0.99	2.4	2.23	0	0.30	"
25A	"	"	"	"	"	6,870	1.00	2.2	2.0	0	0.30	"
26A	"	"	"	"	"	5,880	1.36	1.79	1.54	0	0.32	"
27A	"	"	"	"	"	13,080	0.68	4.61	4.52	0	0.26	HO
1A	3/0	150	12,800	0.85	4	5,610	1.21	1.27	0.94	0		HU
2A	"	"	"	"	"	6,550	1.01	1.51	1.24	0		"
3A	"	"	"	"	"	7,100	0.52	1.65	1.41	0	0.33	"
4A	"	"	"	"	"	7,360	0.48	1.82	1.61	0	0.33	"
5A	3/0	150	12,300	0.88	4	7,650		1.99	1.77	0	0.37	HU
6A	"	"	"	"	"	7,380	0.91	1.82	1.58	0	0.37	HU
7A	"	"	"	"	"	8,340	0.87	2.08	1.87	0	0.34	HS
8A	"	"	"	"	"	11,420	0.75	3.04	2.91	0	0.33	HO
9A	"	"	"	"	"	12,720	0.71	3.32	3.20	0	0.31	HO
10A	"	"	"	"	"	13,500	0.69	3.63	3.52	0	0.31	HO
11A	3/0	150	18,000	0.6	4	7,660	0.92	1.35	1.21	0	0.31	HU
12A	"	"	"	"	"	13,380	0.70	2.92	2.86	0	0.27	HS
13A	3/0	150	24,000	0.45	4	7,480	0.99	0.99	0.88	0	0.29	HS
14A	"	"	"	"	"	13,200	0.71	2.11	2.00	0	0.29	HS
15A	3/0	150	12,800	0.85	8	6,960	1.00	1.20	0.85	−0.19	0.38	DU
16A	"	"	"	"	"	6,720	1.06	1.17	0.80	−0.19	0.38	DU
17A	"	"	"	"	"	6,360	1.12	1.10	0.70	−0.17	0.40	DU
18A	"	"	"	"	"	5,450	1.40	0.98	0.48	−0.1	0.40	DU
19A	"	"	"	"	"	12,780	0.70	2.56	2.42	−0.08	0.36	DS
20A	3/0	150	12,500	0.87	12	6,750	0.98	1.08	0.6			DU
21A	"	"	"	"	"	6,510	1.00	1.04	0.53			DU
22A	"	"	"	"	"	12,500	0.68	2.16	1.86	−0.20	0.34	DU
142A	3/0	300	6,370	6.80	4	5,380	0.99	7.91	4.30	0.16	0.74	RO
143A	"	"	"	"	"	6,400	0.97	8.43	5.46	0.40	0.70	RO
144A	"	"	"	"	"	6,820	0.97	8.7	5.95	0.46	0.70	RO
145A	"	"	"	"	"	7,010	0.93	8.8	6.10	0.46	0.70	RO
146A	"	"	"	"	"	9,010	0.87	10.2	8.23	0.77	0.68	RO
147A	"	"	"	"	"	10,450	0.69	11.4	9.80	0.99	0.60	RO
130A	3/0	300	14,000	3.1	4	5,450	0.87	4.35	2.86	−0.18	0.62	DO
131A	"	"	"	"	"	6,500	0.87	4.95	3.71	−0.18	0.62	DO
132A	"	"	"	"	"	6,670	0.85	5.28	4.14	−0.19	0.62	DO
133A	"	"	"	"	"	7,200	0.95	5.56	4.50	−0.16	0.60	DO
134A	"	"	"	"	"	9,260	0.89	6.66	5.90	0	0.56	HO
135A	"	"	"	"	"	10,580	0.69	7.86	7.23	0	0.56	HO
136A	3/0	300	20,600	2.1	4	7,280	1.08	4.06	3.36	−0.19	0.52	DU
137A	"	"	"	"	"	7,010	0.98	3.85	3.11	−0.17	0.50	DU
138A	"	"	"	"	"	6,540	0.98	3.59	2.79	−0.16	0.48	DU
139A	"	"	"	"	"	5,620	1.04	3.10	2.16	−0.13	0.54	DU
140A	"	"	"	"	"	9,340	1.14	5.10	4.65	0	0.46	HS
141A	"	"	"	"	"	10,800	0.72	6.22	5.85	0	0.44	HS
148A	3/0	300	21,600	2.0	4	5,560	1.01	3.04	2.15	−0.16		DU
149A	"	"	"	"	"	6,560	0.95	3.57	2.82	−0.18	0.50	DU
150A	"	"	"	"	"	6,990	0.97	3.83	3.14	−0.20	0.48	DU
151A	"	"	"	"	"	7,370	0.94	4.01	3.31	−0.20	0.48	DU
152A	"	"	"	"	"	9,250	0.88	5.14	4.68	−0.11	0.46	DS
153A	"	"	"	"	"	10,700	0.67	6.28	5.91	−0.12	0.46	DS
154A	3/0	300	12,700	3.4	8	5,170	1.05	4.15	1.68	−0.40		DU
155A	"	"	"	"	"	6,090	0.99	4.59	2.35	−0.54		DU
156A	"	"	"	"	"	6,520	0.97	4.79	2.62	−0.60		DU
157A	"	"	"	"	"	6,710	0.97	4.92	2.80	−0.65		DU
158A	"	"	"	"	"	8,690	0.95	5.78	4.22	−0.55		DS
159A	"	"	"	"	"	10,020	0.79	6.70	5.35	−0.62	0.62	DO
142B	3/0	450	6,170	15.8	4	5,300	0.99	17.28	8.46	0.71	1.16	RO
143B	"	"	"	"	"	6,260	0.97	17.90	10.45	1.25	1.12	RO
144B	"	"	"	"	"	6,600	0.97	18.3	11.43	1.52	1.12	RO
145B	"	"	"	"	"	6,870	0.93	18.35	11.90	1.85	1.08	RO
130B	3/0	450	12,800	7.6	4	5,400	0.87	9.60	5.31	−0.40	0.92	DO
131B	"	"	"	"	"	6,410	0.87	10.42	6.72	−0.38	0.88	DO
132B	"	"	"	"	"	6,630	0.85	10.77	7.28	−0.33	0.88	DO
133B	"	"	"	"	"	7,030	0.95	11.00	7.67	−0.29	0.86	DO

TABLE III—*Continued*

RESULTS OF TESTS, SHOWING CONDUCTOR MOVEMENTS WITH CABLES HORIZONTALLY SPACED

						Current		Maximum point data				
Test	Cable Size	Span ft.	Tension lb./in.^{2}	Sag ft.	Spacing ft	Amperes	Duration sec.	Radius ft.	Horiz. throw ft.	Vertical movement ft.	Time sec.	Type of movement
136B	3/0	450	21,600	4.5	4	7,100	1.08	7.81	5.99	−0.52	0.76	DU
137B	“	“	“	“	“	6,860	0.98	7.58	5.66	−0.52	0.80	DU
138B	“	“	“	“	“	6,450	0.98	7.30	5.22	−0.46	0.80	DU
139B	“	“	“	“	“	5,460	1.04	6.36	4.04	−0.42	0.80	DU
148B	3/0	450	27,000	3.6	4	5,530	1.01	5.31	3.56	−0.34	0.84	DU
149B	“	“	“	“	“	6,460	0.95	6.23	4.77	−0.40	0.76	DU
150B	“	“	“	“	“	6,870	0.97	6.52	5.10	−0.46	0.72	DU
151B	“	“	“	“	“	7,210	0.94	6.71	5.37	−0.43	0.72	DU
154B	3/0	450	13,500	7.2	8	5,100	1.05	8.84	3.44	−0.94	1.04	DU
155B	“	“	“	“	“	6,000	0.99	9.61	4.64	−1.21	1.00	DU
156B	“	“	“	“	“	6,420	0.97	9.86	5.10	−1.25	0.96	DU
157B	“	“	“	“	“	6,600	0.97	10.11	5.48	−1.32	0.96	DU
23B	3/0	600	12,500	13.8	2	7,040	0.92	19.37	14.3	0.75	0.98	RO
24B	“	“	“	“	“	6,820	0.99	18.68	13.7	1.14	1.00	RO
25B	“	“	“	“	“	6,370	1.00	18.1	12.8	1.00	1.04	RO
26B	“	“	“	“	“	5,520	1.36	17.5	10.75		1.04	RO
1B	3/0	600	12,800	13.5	4	5,470	1.21	16.8	8.65	−0.91	1.21	DO
2B	“	“	“	“	“	6,150	1.01	17.9	10.8	−0.84	1.19	DO
3B	“	“	“	“	“	6,930	0.53	18.2	10.5		1.07	DO
4B	“	“	“	“	“	7,150	0.49	16.95	9.18	−0.78		DO
5B	3/0	600	12,300	14.1	4	7,430	1.+	19.4	12.8	−0.51	1.16	DO
6B	“	“	“	“	“	6,990	0.91	18.75	11.75	−0.51	1.16	DO
11B	3/0	600	18,000	9.6	4	7,140	0.92	15.2	11.0	−0.91	1.04	DS
13B	3/0	600	24,000	7.2	4	7,030	0.99	11.5	8.14	−0.7	0.88	DU
15B	3/0	600	12,800	13.6	8	6,600	1.00	17.9	8.25	−2.38	1.12	DO
16B	“	“	“	“	“	6,510	1.06	17.8	8.0	−2.18	1.15	DO
17B	“	“	“	“	“	6,190	1.12	17.1	6.95	−2.03	1.16	DO
18B	“	“	“	“	“	5,340	1.40	16.35	5.78	−1.72	1.20	DO
20B	3/0	600	12,500	13.9	12	6,610	0.98	17.15	6.04	−2.18	1.16	DO
21B	“	“	“	“	“	6,360	1.00	17.05	5.78	−2.16	1.20	DO
58A	500M	150	12,000	0.9	2	7,620	0.91	1.41	1.09	0	0.34	HS
59A	“	“	“	“	“	8,400	0.98	1.54	1.25	0	0.34	HS
60A	“	“	“	“	“	8,900	0.95	2.11	1.91	0	0.34	HS
61A	“	“	“	“	“	12,680	1.05	2.59	2.45	0.10	0.32	RO
62A	“	“	“	“	“	13,910	1.03	2.90	2.77	0.10	0.32	RO
63A	500M	150	6,370	1.7	4	7,930	0.85	2.04	1.19	0.05	0.48	RO
64A	“	“	“	“	“	11,220	1.03	2.54	1.89	0.07	0.46	RO
65A	“	“	“	“	“	12,900	1.08	2.78	2.20	0.09	0.46	RO
66A	“	“	“	“	“	13,830	1.06	2.92	2.45	0.11	0.44	RO
32A	500M	150	13,500	0.8	4.3	6,020	1.21	0.89	0.39	0		HS
33A	“	“	“	“	“	7,300	0.95	0.97	0.56	0		HS
34A	“	“	“	“	“	7,920	0.87	1.04	0.66	0		HS
35A	“	“	“	“	“	8,570	0.77	1.07	0.72	0		HS
36A	“	“	“	“	“	13,580	0.69	1.82	1.64	0	0.34	HS
37A	500M	150	21,700	0.5	4.2	7,300	0.93	0.62	0.37	0		HS
38A	“	“	“	“	“	7,920	0.87	0.69	0.48	0		HS
39A	“	“	“	“	“	8,540	0.83	0.71	0.51	0		HS
40A	“	“	“	“	“	12,420	0.67	1.14	1.02	0	0.30	HS
41A	“	“	“	“	“	12,420	0.69	1.16	1.04	0		HS
42A	“	“	“	“	“	13,650	0.67	1.24	1.14	0		HS
43A	500M	150	27,100	0.4	4	7,440	0.93	0.52	0.33	0		HS
44A	“	“	“	“	“	8,100	1.01	0.55	0.38	0		HS
45A	“	“	“	“	“	8,690	0.93	0.59	0.44	0		HS
46A	“	“	“	“	“	12,830	1.07	1.01	0.93	0	0.26	HS
47A	“	“	“	“	“	13,610	1.07	1.12	1.05	0	0.26	HS
48A	500M	150	12,000	0.9	8	7,230	0.88	0.97	0.37	0		HS
49A	“	“	“	“	“	8,020	0.88	1.00	0.43	0		HS
50A	“	“	“	“	“	8,450	0.95	1.02	0.48	0		HS
51A	“	“	“	“	“	13,290	1.04	1.37	1.03	0	0.30	HS
52A	“	“	“	“	“	14,100	0.98	1.47	1.17	0		HS

TABLE III—*Continued*

RESULTS OF TESTS, SHOWING CONDUCTOR MOVEMENTS WITH CABLES HORIZONTALLY SPACED

						Current		Maximum point data				
Test	Cable Size	Span ft.	Tension lb./in.^{2}	Sag ft.	Spacing ft	Amperes	Duration sec.	Radius ft.	Horiz. throw ft.	Vertical movement ft.	Time sec.	Type of movement
53A	500M	150	12,000	0.9	11.7	7,140	0.99		small	0		HS
54A	"	"	"	"	"	7,760	1.03	0.95	0.3	0		HS
55A	"	"	"	"	"	8,180	1.01	0.95	0.32	0		HS
56A	"	"	"	"	"	13,200	1.05	1.16	0.74	0		HS
57A	"	"	"	"	"	14,300	1.03	1.26	0.88	0		HS
58B	500M	600	12,400	14.0	2.1	7,100	0.91	15.29	5.9	0.5	1.12	RO
59B	"	"	"	"	"	7,770	0.98	15.68	8.33	0.58	1.12	RO
60B	"	"	"	"	"	8,250	0.95	15.8	8.9	0.75	1.12	RO
32B	500M	600	12,300	14.1	4.3	5,870	1.21	14.63	3.92	0	1.28	HO
33B	"	"	"	"	"	6,980	0.95	15.08	5.26	0	1.24	HO
34B	"	"	"	"	"	7,530	0.87	15.2	5.7	0	1.24	HO
35B	"	"	"	"	"	8,140	0.77	15.37	6.10	0	1.20	HO
37B	500M	600	18,700	9.2	4.2	6,990	0.93	9.9	3.7	0	1.04	HS
38B	"	"	"	"	"	7,550	0.87	10.22	4.49	0	1.00	HS
39B	"	"	"	"	"	8,190	0.83	10.39	4.85	0	1.00	HS
43B	500M	600	24,400	7.1	4.0	7,310	0.93	7.83	3.32	0	0.96	HS
44B	"	"	"	"	"	7,790	1.01	8.05	3.80	0	0.96	HS
45B	"	"	"	"	"	8,400	0.93	8.20	4.11	0	0.92	HS
48B	500M	600	12,400	14.0	8	7,160	0.88	14.65	3.65	−0.19	1.28	DO
49B	"	"	"	"	"	7,880	0.88	14.8	4.09	−0.25	1.28	DO
50B	"	"	"	"	"	8,210	0.95	14.92	4.47	−0.25	1.28	DO
53B	500M	600	12,600	13.7	11.4	7,070	0.99	14.3	2.83	−0.32		DO
54B	"	"	"	"	"	7,580	1.03	14.42	3.12	−0.36	1.32	DO
55B	"	"	"	"	"	7,940	1.01	14.57	3.48	−0.43	1.32	DO
106A	No. 2	150	12,000	0.9	4	4,650	1.06	2.23	1.78	−0.44	0.38	DU
107A	"	"	"	"	"	5,290	1.10	2.56	2.18	−0.44	0.37	DU
108A	"	"	"	"	"	5,370	1.06	2.58	2.21	−0.44	0.36	DU
109A	"	"	"	"	"	5,470	1.10	2.72	2.34	−0.49	0.36	DU
28A	No. 2	150	12,600	0.86	4	6,020	1.40	2.96	2.56	−0.6	0.42	DU
29A	"	"	"	"	"	7,760	0.50	3.81	3.64	−0.22	0.36	DU
30A	"	"	"	"	"	11,720	0.70	6.55	6.44	−0.33	0.32	DS
31A	"	"	"	"	"	4,790	2.60	2.77	2.19	−0.8	0.44	DU
102A	No. 2	150	13,500	0.8	4	7,820	0.71	3.74	3.61	−0.19	0.32	DS
103A	"	"	"	"	"	9,950	0.40	5.45	5.35	−0.24	0.32	DS
104A	"	"	"	"	"	10,600	0.42	6.24	6.16	−0.25	0.30	DS
105A	"	"	"	"	"	11,750	0.38	7.09	7.01	−0.25	0.29	DS
96A	No. 2	150	18,000	0.6	4	7,760	0.42	2.87	2.76	−0.19	0.30	DU
97A	"	"	"	"	"	9,850	0.40	4.25	4.16	−0.27	0.28	DU
98A	"	"	"	"	"	10,770	0.42	4.67	4.58	−0.33	0.27	DU
99A	"	"	"	"	"	11,750		5.28	5.20	−0.32	0.27	DU
100A	"	"	"	"	"	3,700		1.01	0.72	−0.11		DU
83A	No. 2	150	12,000	0.9	8	5,540	0.40	1.98	1.47	−0.42	0.42	DU
84A	"	"	"	"	"	7,690	0.44	3.14	2.74	−0.68	0.42	DU
85A	"	"	"	"	"	8,920	0.42	4.13	3.79	−0.74	0.42	DU
86A	"	"	"	"	"	9,820	0.42	4.75	4.42	−0.84	0.42	DU
87A	"	"	"	"	"	10,200	0.44	5.15	4.85	−0.84	0.42	DU
88A	"	"	"	"	"	10,500	0.42	5.44	5.16	−0.93	0.41	DU
89A	"	"	"	"	"	10,700	0.42	5.91	5.59	−1.05	0.41	DU
90A	"	"	"	"	"	10,810	0.42	6.75	6.48	−1.05	0.41	DU
91A	No. 2	150	18,000	0.6	8	7,580	0.44	2.04	1.83	−0.29	0.36	DU
92A	"	"	"	"	"	9,650	0.42	3.34	3.16	−0.46	0.38	DU
93A	"	"	"	"	"	10,500	0.40	4.15	3.99	−0.58	0.37	DU
94A	"	"	"	"	"	11,300	0.40	4.82	4.62	−0.79	0.38	DU
95A	"	"	"	"	"	3,620	0.63	1.01	0.48	−0.29		DU
77A	No. 2	150	12,000	0.9	11.6	4,490	0.44	2.16	1.01	−1.01	0.48	DU
78A	"	"	"	"	"	5,150	0.38	2.62	1.34	−1.2	0.44	DU
79A	"	"	"	"	"	5,350	0.42	3.08	1.68	−1.68	0.46	DU
80A	"	"	"	"	"	5,470	0.40	3.08	1.68	−1.68	0.46	DU
81A	"	"	"	"	"	5,280	0.44	1.76	1.12	−0.45	0.50	DU
82A	"	"	"	"	"	..	..	..	..	..	..	DU

TABLE III—*Continued*

RESULTS OF TESTS, SHOWING CONDUCTOR MOVEMENTS WITH CABLES HORIZONTALLY SPACED

Test	Cable Size	Span ft.	Tension lb./in.^{2}	Sag ft.	Spacing ft.	Current		Maximum point data				
						Amperes	Duration sec.	Radius ft.	Horiz. throw ft.	Vertical movement ft.	Time sec.	Type of movement
106B	No. 2	600	12,000	14.5	4	4,350	1.06	24.4	13.58	−5.83	1.20	DU
107B	"	"	11,800	14.7	"	4,810	1.10	27.0	16.4	−6.82	1.20	DU
108B	"	"	11,500	15.1	"	4,900	1.06	27.7	17.1	−6.70	1.20	DU
109B	"	"	11,400	15.2	"	4,920	1.10	27.7	17.0	−6.75	1.20	DU
28B	No. 2	600	12,600	13.7	4	Hit ground						
31B	"	"	"	"	"	"	"					
100B	No. 2	600	18,800	9.2	4	3,600		14.9	7.81	−3.52	1.12	DU
101B	"	"	"	"	"	4,470	0.79	18.6	10.70	−5.99	1.12	DU
95B	No. 2	600	18,200	9.5	8	3,570	0.63	14.7	4.79	−4.41	1.12	DU
77B	No. 2	600	12,100	14.3	11.8	4,460	0.44	19.8	4.84	−4.96	1.16	DS
78B	"	"	"	"	"	5,150	0.38	20.4	5.59	−5.33	1.12	DS
79B	"	"	12,300	14.1	"	5,300	0.42	21.1	6.58	−5.95	1.12	DS
80B	"	"	12,400	14.0	"	5,470	0.40	21.0	6.51	−5.95	1.08	DS
73A	4/0 WP	150	5,900	2.3	1.5	8,150	0.99	3.78	3.23	0.35	0.36	RO
74A	"	"	"	"	"	10,890	1.05	4.71	4.35	0.49	0.32	RO
75A	"	"	"	"	"	12,820	1.11	5.19	4.89	0.54	0.31	RO
76A	"	"	"	"	"	13,450	1.07	5.62	5.38	0.65	0.31	RO
72A	4/0 WP	150	10,400	1.3	1.5	13,320	1.05	4.24	4.07	0.16	0.27	RO
71A	4/0 WP	150	13,500	1.0	1.5	13,400	1.03	3.98	3.86	0	0.26	HO
67A	4/0 WP	150	16,900	0.8	1.5	8,110	0.85	2.20	2.05	0	0.3	HO
68A	"	"	"	"	"	10,920	1.03	3.07	2.96	0	0.26	HO
69A	"	"	"	"	"	12,605	1.09	3.44	3.34	0	0.26	HO
70A	"	"	"	"	"	13,300	1.05	3.90	3.82	0	0.26	HO

NOTE: In the column headed "Cable Size," the symbol M means thousand circular mils, while WP means weather-proof.

θ = Temperature rise in degrees fahrenheit during time t.

T = Tension in cable in pounds per square inch.

T_1 = Initial tension in cable in pounds per square inch.

T_2 = Tension in cable at point of maximum deflection, in pounds per square inch.

λ = Length of cable along catenary in feet.

λ_0 = Unstressed length of cable at initial temperature.

λ_1 = Initial length of cable.

λ_2 = Length of cable when at maximum deflection.

X = Horizontal distance moved by conductor, in feet.

X_c = Horizontal distance moved by cable at center of span, in feet.

X_m = Maximum horizontal distance moved by cable at center of span, in feet.

y_0 = Initial sag at center of span in feet.

A sketch showing the principal dimensional symbols is given in Fig. 36.

From Equation (2), the magnetic force per foot of conductor, when each conductor has moved a distance X from its initial position, is:

$$F = \frac{0.045\, I^2}{10^6\,(2\,X + C)} \tag{2.1}$$

The energy imparted to the conductor by this force for the entire span is given by

$$\text{Input energy (ft-lb.)} = L \int_0^{X_m} \frac{0.045\, I^2}{10^6\,(2\,q\,X_c + C)}\, d\,X_c \tag{2.2}$$

The value q is to be evaluated later semi-empirically. The solution of the above integral gives:

$$\text{Input energy} = L\ \frac{0.045\, I^2}{10^6} \cdot \frac{1}{2} \log_e \left(\frac{C + 2\,q\,X_m}{C} \right) \tag{2.3}$$

The energy stored in the conductor due to its stretching is given by the product of the average tension and its change in length. Thus:

$$\text{Stored energy (ft-lb.)} = B\ \frac{T_1 + T_2}{2}\ (\lambda_2 - \lambda_1) \tag{2.4}$$

The energy calculated by equation **2.3** and that calculated by equation **2.4** may be equated. This will be done after the various parts of equation **2.4** have been determined.

According to the parabolic sag formulas, the length of cable at any sag is given by

$$\lambda = L + \frac{8}{3\,L} R^2 \text{ ("Std. Handbook for Elec. Eng.", page 966, 1922 Ed.)} \tag{2.5}$$

Therefore the change in length is

$$\lambda_2 - \lambda_1 = \left(L + \frac{8}{3\,L} R_m^2\right) - \left(L + \frac{8}{3\,L} y_0^2\right)$$

$$= \frac{8}{3\,L} (R_m^2 - y_0^2) \tag{2.6}$$

TABLE IV
RESULTS OF TESTS, SHOWING CONDUCTOR MOVEMENTS WITH CABLES VERTICALLY SPACED

Test	Cable size	Span ft.	Tension lb./in.^{2}	Sag ft.	Spacing ft.	Current		Maximum movement data			
								Upper wire		Lower wire	
						Amperes	Duration sec.	Throw ft.	Time sec.	Throw ft.	Time sec.
110A	3/0	150	12,000	0.9	4	5,380	0.80	0.79		0.59	
111A	“	“	“	“	“	6,375	0.90	1.16		0.84	
112A	“	“	“	“	“	6,840	0.86	1.33		0.91	
113A	“	“	“	“	“	7,180	0.82	1.50		0.99	
114A	“	“	“	“	“	12,450	0.61	4.05		2.20	
115A	3/0	150	18,000	0.6	4	5,580	0.83	0.64		0.59	
116A	“	“	“	“	“	6,670	0.80	0.94		0.89	
117A	“	“	“	“	“	7,090	0.91	1.08		0.89	
118A	“	“	“	“	“	7,350	0.89	1.20		0.99	
119A	“	“	“	“	“	13,000	0.57	3.26		2.19	
200A	3/0	300	12,000	3.6	2	5,600		3.77	0.60	2.65	
201A	“	“	“	“	“	7,500		6.35	0.70	3.84	0.40
202A	“	“	“	“	“	11,000		11.25	0.64	5.75	0.36
197A	3/0	300	24,000	1.8	2	5,600		2.94	0.42	2.54	
198A	“	“	“	“	“	7,500		4.50	0.44	3.70	
199A	“	“	“	“	“	11,000		7.80	0.54	5.95	
160A	3/0	300	12,400	3.5	4	5,550	1.05	2.00		1.55	
161A	“	“	“	“	“	6,450	0.97	2.71		2.04	
162A	“	“	“	“	“	6,990	0.97	2.98		2.19	
163A	“	“	“	“	“	7,220	0.95	3.29		2.35	
164A	“	“	“	“	“	9,175	0.93	8.47	1.02	3.18	
165A	“	“	“	“	“	10,620	0.69	11.22	1.	4.20	
166A	3/0	300	17,300	2.5	4	5,440	0.82	2.09		1.55	
167A	“	“	“	“	“	6,480	0.77	2.97		2.04	
168A	“	“	“	“	“	6,880	0.79	3.46	0.62	2.19	
169A	3/0	300	17,300	2.5	4	7,140	0.79	3.80	0.66	2.32	
170A	“	“	“	“	“	9,200		6.30	0.68	3.16	
171A	“	“	“	“	“	10,470	0.73	8.77	0.74	3.90	
194A	3/0	300	18,000	2.4	8	5,300		0.99		1.36	
195A	“	“	“	“	“	6,800		1.78		2.09	
196A	“	“	“	“	“	10,000		3.46		5.14	
191A	3/0	300	21,600	2.0	8	5,300		0.90		1.29	
192A	“	“	“	“	“	6,800		1.52		2.05	
193A	“	“	“	“	“	10,000		3.50		3.62	
200B	3/0	450	12,000	8.1	2	5,600		3.50	0.72	3.50	0.56
201B	“	“	“	“	“	7,500		5.77	0.88	4.95	0.52
197B	3/0	450	24,400	4.0	2	5,600		4.81	0.64	3.96	
198B	“	“	“	“	“	7,500		7.60	0.72	5.79	0.56
160B	3/0	450	13,500	7.2	4	5,550	1.05	2.34		3.00	
161B	“	“	“	“	“	6,450	0.97	3.04		3.84	
162B	“	“	“	“	“	6,990	0.97	3.18	0.60	4.03	
163B	“	“	“	“	“	7,220	0.95	3.50		4.37	
166B	3/0	450	21,600	4.5	4	5,440	0.82	3.09		3.14	
167B	“	“	“	“	“	6,480	0.77	4.16		4.06	
168B	“	“	“	“	“	6,880	0.79	4.70		4.44	
169B	“	“	“	“	“	7,140	0.79	5.20		4.70	
194B	3/0	450	18,700	5.2	8	5,300		1.68		2.30	
195B	“	“	“	“	“	6,800		2.85		4.00	
191B	3/0	450	23,800	4.1	8	5,300		1.68		2.31	
192B	“	“	“	“	“	6,800		2.71		4.42	
110B	3/0	600	12,200	14.2	4	5,250	0.80	2.04		3.22	
111B	“	“	“	“	“	6,100	0.90	2.52	0.64	4.13	
112B	“	“	“	“	“	6,500	0.86	2.58	0.64	5.04	
113B	“	“	“	“	“	6,850	0.82	2.58		4.39	
115B	3/0	600	17,500	9.9	4	5,370	0.83	3.90		4.16	
116B	“	“	“	“	“	6,300	0.80	5.03		5.22	
117B	“	“	“	“	“	6,710	0.91	5.56	0.80	5.62	
118B	“	“	“	“	“	6,900	0.89	5.56	0.80	5.54	

TABLE IV—*Continued*

RESULTS OF TESTS, SHOWING CONDUCTOR MOVEMENTS WITH CABLES VERTICALLY SPACED

						Current		Maximum movement data			
								Upper wire		Lower wire	
Test	Cable size	Span ft.	Tension lb./in.^{2}	Sag ft.	Spacing ft.	Amperes	Duration sec.	Throw ft.	Time sec.	Throw ft.	Time sec.
120A	500M	150	13,500	0.8	4	6,070	0.81	0.35		0.33	
121A	"	"	"	"	"	7,290	0.91	0.50		0.46	
122A	"	"	"	"	"	8,080	0.91	0.56		0.50	
123A	"	"	"	"	"	8,400	0.87	0.66		0.56	
124A	"	"	"	"	"	13,750	0.59	1.76		1.18	
125A	500M	150	18,000	0.6	4	5,900	0.86	0.28		0.28	
126A	"	"	"	"	"	7,250	1.00	0.39		0.39	
127A	"	"	"	"	"	7,880	0.95	0.46		0.42	
128A	"	"	"	"	"	8,400	0.96	0.51		0.51	
129A	"	"	"	"	"	13,750	0.59	1.30		1.02	
212A	500M	300	11,100	3.9	2	6,000		1.68		1.29	
213A	"	"	"	"	"	9,000		2.96	0.56	2.06	
214A	"	"	"	"	"	11,800		5.41	0.66	3.10	0.38
209A	500M	300	19,600	2.2	2	6,000		1.19		1.35	
210A	"	"	"	"	"	9,000		2.26		2.00	
211A	"	"	"	"	"	11,800		3.74		3.10	
206A	500M	300	12,700	3.4	8	5,400		0.45		0.45	
207A	"	"	"	"	"	7,700		0.88		0.84	
208A	"	"	"	"	"	11,000		2.05		1.72	
203A	500M	300	21,600	2.0	8	5,400		0.39		0.39	
204A	"	"	"	"	"	7,700		0.71		0.71	
205A	"	"	"	"	"	11,000		1.42		1.29	
212B –	500M	450	12,300	7.9	2	6,000		2.30	0.76	1.95	0.56
213B	"	"	"	"	"	9,000		3.84	0.88	2.93	0.56
209B	500M	450	24,400	4.0	2	6,000		2.16	0.60	1.98	0.56
210B	"	"	"	"	"	9,000		3.66	0.60	3.15	0.56
206B	500M	450	12,300	7.9	8	5,400		0.89		0.47	
207B	"	"	"	"	"	7,700		1.22		1.22	
203B	500M	450	23,800	4.1	8	5,400		0.76		0.82	
204B	"	"	"	"	"	7,700		1.24		1.37	
120B	500M	600	12,700	13.7	4	5,840	0.81	1.42		1.78	
121B	"	"	"	"	"	7,040	0.91	2.02	0.80	2.02	
122B	"	"	"	"	"	7,800	0.91	2.13	0.80	2.82	
123B	"	"	"	"	"	8,050	0.87	2.32	0.80	2.52	
125B	500M	600	17,900	9.7	4	5,790	0.86	1.87		1.68	
126B	"	"	"	"	"	7,010	1.00	2.52		2.45	
127B	"	"	"	"	"	7,600	0.95	2.90		2.58	
128B	"	"	"	"	"	7,760	0.96	3.13		2.18	

The length of the cable when strung is

$$\lambda_1 = L + \frac{8}{3\,L}\,y_0^2 \qquad (2.7)$$

which is the unstressed length plus the stretch due to the tension developed. The stretch is $L\,T_1/E$, so the initial unstressed length can be written:

$$\lambda_0 = L + \frac{8}{3\,L}\,y_0^2 - \frac{T_1}{E}\,L \qquad (2.8)$$

The unstressed length after any temperature change θ can be taken as $\lambda_0 + L\,\alpha\,\theta$. T_2 may be calculated from the relation that the tension is $(E/L) \times$ stretch.

Therefore $$T_2 = \frac{E}{L}\,(\lambda_2 - \lambda_0 - L\,\alpha\,\theta) \qquad (2.9)$$

substituting the value for λ_2 as obtained from equation (2.5), and the value of λ_0 from equation (2.8), the following is obtained.

$$T_2 = \frac{E}{L}\left(L + \frac{8}{3\,L}\,R_m^2 - L - \frac{8}{3\,L}\,y_0^2 + \frac{T_1}{E}\,L - L\,\alpha\,\theta\right) \qquad (2.10)$$

$$T_2 = E\left[\frac{8}{3\,L^2}\,(R_m^2 - y_0^2) + \frac{T_1}{E} - \alpha\,\theta\right] \qquad (2.11)$$

Since the sag can be expressed as $y_0 = K_0\,m\,L^2/8\,T_1$ (see page 966 of "Standard Handbook for Elec. Eng.," 1922 Edition), then $8/3\,L^2$ may be written $K_0\,m/3\,y_0\,T_1$. The equation for T_2 may now be written in its final form

$$T_2 = E\left[\frac{K_0\,m}{3\,T_1}\left(\frac{R_m^2 - y_0^2}{y_0}\right) + \frac{T_1}{E} - \alpha\,\theta\right] \qquad (2.12)$$

The area of the conductor in square inches is converted to circular mils by

$$B = A/1.272 \times 10^6 \qquad (2.13)$$

Substituting the values from equations, (**2.13**), (**2.12**), and (**2.6**) into equation (**2.4**), and equating that to equation (**2.3**), the following expression is obtained:

$$L\,\frac{0.045\, I^2}{10^6}\cdot\frac{1}{2}\log_e\frac{C+2\,q\,X_m}{C}$$

$$= \frac{A}{1.272\times 10^6}\cdot\frac{1}{2}\left[T_1 + \frac{E\,K_0\,m}{3\,T_1}\left(\frac{R_m^2 - y_0^2}{y_0}\right)\right.$$

$$\left. + T_1 - E\,\alpha\,\theta\right]\left[\frac{8}{3\,L}\,(R_m^2 - y_0^2)\right] \qquad (2.14)$$

Dividing through by L and substituting $K_0\,m/3\,y_0\,T_1$ for $8/3\,L^2$ and rearranging terms, the following is obtained.

$$\frac{0.0572\,\dfrac{I^2}{A}\log_e\dfrac{C+2\,q\,X_m}{C}}{\dfrac{K_0\,m}{3}\left(\dfrac{R_m^2 - y_0^2}{y_0}\right)}$$

$$= \frac{E\,K_0\,m}{3\,T_1^2}\left(\frac{R_m^2 - y_0^2}{y_0}\right) + 2 - \frac{E}{T_1}\,\alpha\,\theta \qquad (2.15)$$

In this equation the values for q and θ have yet to be determined. They will be determined for copper cables.

The resistance of 97.3 per cent conductivity copper cable at some temperature θ above 68 deg. fahr. is given by

$$r = (1 + 0.00212\,\theta)\,\frac{10.65}{A}$$

Let $d\,t$ and $d\,\theta$ be elementary increases in time and temperature, respectively. Then, taking the specific heat of copper as 0.093, and the weight of copper cable as being $3.09/10^6$ lb. per cir. mil ft., and 1 watt-hr. as 3.41 B. t. u.:

$$\frac{3.41}{3600}\,I^2\,(1 + 0.00212\,\theta)\,\frac{10.65}{A}\,d\,t$$

$$= \frac{3.09\,A}{10^6}\,0.093\,d\,\theta \qquad (2.16)$$

Transposing, integrating, and writing the solution, the following expression is obtained:

$$t = 0.01342\,\frac{A^2}{I^2}\log_e(1 + 0.00212\,\theta) \qquad (2.17)$$

from which

$$\theta = 471.5\,\left(e^{74.5\frac{I^2}{A}{}^2 t} - 1\right) \qquad (2.18)$$

and the last term of equation (**2.15**) becomes

$$\frac{14{,}000{,}000 \times 0.0000096\,\theta}{T_1} = \frac{63{,}400}{T_1}\,\left(e^{74.5\,\frac{I^2}{A^2}t} - 1\right) \qquad (2.19)$$

This expression is cumbersome to use, so a simpler expression that gives results that are within 5 per cent error from the correct value of this term was determined empirically. It can be used up to values of $I^2\,t/A^2$ of 0.004. The empirical expression is:

$$\frac{E\,\alpha\,\theta}{T_1} = 5.13 \times 10^6\,\frac{I^2\,t}{A^2\,T_1} \qquad (2.20)$$

The value of t still remains unknown. A study of the time to reach the point of maximum deflection was made and the purely empirical formulas given in equation (**3**) and (**3.1**) in the main part of the paper resulted. The term given in equation (**2.20**) is a correction term in the main formula, and even errors of ten per cent or more in it are usually unimportant.

The determination of the value of the term q will now be taken up. Referring to equation (**2.3**), it is evident that the energy input for a movement X is $(0.0225\,I^2/10^6)\,\log_e[\,(C + 2\,X)/C\,]$ per linear foot.

If we assume that a cable retains its parabolic form throughout its movement, then the horizontal projection is also a parabola, and the value of X at a distance l from the mid-point of the span is:

$$X = X_m - p\,l^2 \qquad (2.21)$$

where p is a proportionality constant. The average input for the entire span is then:

Input per ft.

$$= \frac{0.0225\,I^2}{10^6}\;\frac{\displaystyle\int_0^{L/2}\log_e\frac{C+2(X_m - p\,l^2)}{C}\,d\,l}{L/2} \qquad (2.22)$$

It can be shown that the solution of equation (**2.22**) is:

$$\text{Input per ft.} = \frac{0.0225\,I^2}{10^6}\,\sqrt{\frac{1}{\dfrac{2\,X_m}{C + 2\,X_m}}}$$

$$\left[\log_e\left(\frac{1 + \sqrt{\dfrac{2\,X_m}{C + 2\,X_m}}}{1 - \sqrt{\dfrac{2\,X_m}{C + 2\,X_m}}}\right) - 2\sqrt{\frac{2\,X_m}{C + 2\,X_m}}\,\right] \qquad (2.23)$$

This value of energy when multiplied by L, can be equated to that expressed in equation (**2.3**). A direct solution for q is not simple. It can be observed that the value for q would vary for different values of X_m/C. It is found, however, that for a wide range of variation in this ratio, the value of q changes very slowly. For example, the following table shows the comparison:

X_m/C	q
10.0	0.57
1.0	0.62
0.1	0.66

These results indicate that about 1.25 would be a good value to use for $2q$ in equation (**2.3**). However, because of the fact that the loading due to the magnetic forces is greater near the supports, the cable departs from the catenary or parabola, and has greater sag near the supports than a true catenary. This means that the average energy input is increased above that calculated. The exact amount of this increase, and corresponding value of $2q$, is probably difficult to determine mathematically.

It has just been shown that it should be greater than 1.25, and of course it must be less than 2, since this is the value it would have if the cable hung in a rectangular form, that is, with a constant sag for its entire length. Obviously, the cable remains closer to being a catenary in form rather than a rectangle, so the above values should be closer to 1.25. The value need not be very precise, because, being a logarithmic term, it can be varied considerably without affecting the final result very much. It was found that the use of $2q = 1.5$ gave quite good agreement between calculated and experimental results, so this figure was chosen.

If the value in equation (**2.20**) and the above value for $2q$ is substituted in equation (**2.15**), and if m is taken as 3.85 and E as 14,000,000 (values for copper), then the following expression is obtained.

$$\frac{0.0447\, y_0 \frac{I^2}{A} \log_e \frac{C + 1.5\, X_m}{C}}{K_0\,(R_m^2 - y_0^2)} = \frac{18 \times 10^6\, K_0}{T_1^2}\left(\frac{R_m^2 - y_0^2}{y_0}\right) + 2 - 5.13 \times 10^6 \frac{I^2\, t}{A^2\, T_1} \tag{2.24}$$

Since R_m and X_m are both unknown, this equation cannot be solved directly. However, for the great majority of cases, the path of the cable is horizontal, or nearly so. Assuming horizontal movement, then:

$$R_m = \sqrt{X_m^2 + y_0^2} \tag{2.25}$$

By substituting this in equation (**2.24**), the following usable form is obtained.

$$\frac{0.0447\, y_0 \frac{I^2}{A} \log_e \frac{C + 1.5\, X_m}{C}}{K_0\, X_m^2} = \frac{18 \times 10^6\, K_0\, X_m^2}{T_1^2\, y_0} + 2 - 5.13 \times 10^6 \frac{I^2\, t}{A^2\, T_1} \tag{2.26}$$

Equation (**2.26**) is the same as equation (**5**) in the main part of the paper.

Appendix D.

MINIATURE TESTS

As explained in the main part of the paper, the conditions of the miniature test should be so chosen that each of the terms in equation (**5**) will be the same as for the large scale condition being duplicated. This conclusion was reached because of the fact that equation (**5**) contains the constant term 2, and if one term is the same it is reasonable to suppose that all terms should be the same. Let n, n_i, n_t, and n_a be the multipliers of the full scale distances, current, tension, and area of cable, respectively, to obtain the equivalent small scale values, and substitute $\sqrt{y_0}/3$ for t. Then in order to keep the respective terms of equation (**5**), the same for both full scale and small scale values, the following relations must hold:

$$\frac{n\, n_i^2}{n^2\, n_a} = 1 \qquad \text{(From left hand term)}$$

$$\frac{n^2}{n_t^2\, n} = 1 \qquad \text{(From first right hand term)}$$

$$\frac{n_i^2 \sqrt{n}}{n_a^2\, n_t} = 1 \qquad \text{(From last term)}$$

The solution of these three simultaneous equations gives:

$$n_i = n_a = n$$
$$n_t = \sqrt{n}$$

Since $y_0 = K_0\, m\, L^2/8\, T_1$, $L = \sqrt{8\, T_1\, y_0/K_0\, m}$

The multiplier for span length, then, is:

$$\sqrt{n_t\, n} = \sqrt{n^{3/2}} = n^{3/4}$$

Discussion

E. F. Pearson: The Northwestern Electric Company in Portland has had several cases of heavy conductors on three-phase 11,000-volt lines slapping together while carrying short-circuit currents of from 5000 to 14,000 amperes. Our case seems to parallel closely some of the test cases as set up in the paper.

Since reading the paper I have been wondering just what will be the best economic solution of this problem as applied to our existing systems within city limits.

The paper recommends as a solution the spacing of poles at closer intervals, the use of heavier conductors, higher stringing tensions, the use of feeder reactors to limit the current, and increased spacing of conductors. In our city, and the same condition should apply in other large cities, the pole spacing in general is practically as low as city regulations will permit. Additional poles on residential and business streets are objectionable and I do not look for much relief from this source.

The use of conductors of much larger than 4/0, together with heavier stringing tensions, results in considerable increase in guying costs and in many cases it is impractical to install additional guys at dead ends due to protests from property owners. A certain amount of relief, however, may be obtained from this source, more particularly where present conductors are very light, such as changing from No. 4 to No. 1/0 copper.

Since the magnetic force between conductors is proportional to the square of the current, it seems to me that limiting of current with reactance, either in the form of reactors or high-reactance transformers, offers the best economic solution.

Some relief can also be obtained through the increase of conductor spacing, but at considerable cost on existing lines.

One other possible solution for lines of 13 kv. or less in congested urban territories has occurred to me. Since the conductors are repelled from one another under short-circuit conditions, we might consider the installation of a semi-rigid string of small strain insulators between conductors at the center of existing spans.

This idea at first may seem far-fetched. However, this should, to a certain degree, act as a substitute for decreased pole spacing and thus minimize the conductor movement. The cost of installation would be considerable, but for 13 kv. and less, it should not cost over one-third of the value of an intermediary pole, particularly for the long poles necessary in congested districts.

Whatever plan we use to effect a complete solution on systems already existing in our city will cost a considerable amount of money and the one which will best effect the solution on an economic basis should be the one chosen.

L. R. Gamble: We have already checked up some of the lines on our system with the data presented in this paper, and find we are still safe with the higher voltage lines like 110,000 and 60,000, but we are getting dangerously close with our 13,000-volt lines.

A. C. Pratt: We have a great deal of rather heavy distribution at 2300 volts. The short-circuit values can reach probably 25,000 amperes with reactors in series, and on lines without reactors can reach 50,000 or 60,000 amperes. So far we have got along pretty well by the use of spreaders. For that low voltage our spreaders are exceedingly simple, being nothing but ordinary cross-arms and ordinary pins, the same as a pole structure without the pole. They hang in the middle of the span. The spans are about 110 ft., and this spreader cuts the effective span down to about 55 ft. Inasmuch as the maximum short circuit, of course, is considerably greater in the immediate vicinity of the substation, we have recently adopted the expedient of using weather-proof wire for, say, 500 ft. outside the substation, at the same time using large cables, say 500,000 or 600,000 cir. mils for this same distance. Beyond this point we split up into a number of smaller cables in order to reduce the inductive drop.

We have one case of a short 2300-volt tie between substations, which acts to tie the buses of the substations together, making, in effect, one station.

There are two circuits on this pole line. Each circuit is 633,000 cir. mils. The spreaders on those circuits are 50 ft. apart. We have never yet had a flash on these lines, although I have no doubt we reach 50,000 amperes.

L. F. Hunt: In designing one of our long spans of multi-circuit type over the Long Beach Channel the slapping of conductors together, due to short circuits, was considered. We took steps to calculate what effect the heavy short-circuit currents would have on that span. It was found that a single-phase short circuit, that is, one conductor short-circuited with the other conductor, gave the most severe condition. It was also found that the temperature rise in the conductor due to the heating of the current, caused considerable sag in the span, which would give considerable trouble if the spacing was not vertical. The spacing in these spans being vertical, the sag would cause a short circuit on the same circuit, therefore causing the same circuit breaker to trip out.

It was also found that by selecting the circuits so they could be relayed at an increased rate, the amount of swing of conductors would be reduced and furthermore that the heavier conductor would decrease the swing. Due to the fact that it took a very peculiar coincident short circuit to cause sufficient current to flow, and the short circuit had to be on one particular feeder to give any trouble, the standard conductor was used.

L. J. Corbett: I wish to add a word regarding the three-phase short circuit. It is my opinion that no greater swing of conductors would be experienced from full metallic short circuits on three-phase lines than from the single-phase short circuits considered in the paper. The frequencies in common use are 25 and 60 cycles per second. Because of their inertia the conductors will not get into motion soon enough to give any trouble from their displacement, due to the rapidly reversing forces which would exist when all three phases are involved. In the single-phase short circuit there is a succession of impulses, each tending to force the conductors apart, since the current in the two wires is flowing in opposite directions on both sides of the cycle, so the effect is cumulative.

I believe the authors have discussed the maximum condition by considering a single-phase short circuit between two of the conductors.

W. S. Peterson: I agree with Mr. Pearson that it is best, in general, to use reactors to cut down the currents and thus reduce the forces on the conductors, because you are then working with a factor that varies as the square. It is the same principle that makes the use of shorter spans valuable, because the movements vary approximately as the 3/2 power of the span, while the variation with other factors is at a lower power. This leads to the point that has been mentioned, that is, putting insulators at the center of the span, thus dealing with the next most effective thing, namely, span length.

I have seen the insulators so installed on the Montana Power Company system. I believe this method is of value and should be used at times. The only objection that I have ever heard against it, is that it is difficult to maintain the insulators. On the other hand, such work is infrequent on low-voltage circuits, and if the conductors are heavy enough so that some sort of a trolley can be used to transport the men out to the center of the span on the conductor, it should still be an effective method of limiting conductor movements.

Mr. Wade is correct in assuming that in some cases the movement is so extreme that the stresses are close to the elastic limit of the cable. Equation (2.12) in Appendix C of the complete paper can be used to calculate this maximum tension. In some cases, however, the elongation due to heating decreases the tension more than increased radial sag has increased it, so that the tension at the point of maximum deflection is not higher than the initial tension.

The three-phase short circuits, of course, open up a new field, possibly more complicated than the single-phase condition. In brief, in the three-phase condition, one is dealing with a conductor carrying a current in the magnetic field set up by currents in the other two conductors. These currents are out of phase, which makes the problem more complicated mathematically. I believe that, in three-phase investigations, the thing to do is to use the miniature test set-up, which should give results quicker and more accurately than a system of calculation.

In the case of the Long Beach Channel crossing mentioned by Mr. Hunt, I imagine the reduction in the time to trip the breakers might be a distinct help. I said in the paper that in general the circuit breakers could not be tripped fast enough to be of help. I was referring to spans of the order of 150 ft. in length where the time to reach the maximum point is one-quarter to one-third of a second. In the Long Beach Channel crossing, the spans are over 1000 ft. and the time to reach the maximum point is much longer. If one or two seconds should elapse before the maximum deflection is reached, the circuit breaker can be of use and the movement would be reduced by tripping more quickly.

The vertical construction of these lines is an advantage, as it would have a tendency to confine the interference to the circuit in trouble, unless resulting arcs are blown into adjacent circuits, or unless the movements should acquire horizontal components from the currents in the adjacent circuits.

Residual Voltages and Currents in Power Systems

BY L. J. CORBETT[1]
Member, A. I. E. E.

Synopsis.—In the problem of inductive coordination of power and communication systems, residual voltages and currents in the power lines are an important element, yet it is apparent that they are not in general well understood, Studies have been made and others are under way by well-equipped organizations, which will add much to the data concerning them. In this paper the general principles which apply are briefly reviewed and applied to typical power circuits and networks, and oscillograms are shown which verify the theory presented.

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BALANCED AND RESIDUAL VOLTAGES AND CURRENTS

In the ideal three-phase circuit the vector sum of the voltages to ground of the phase wires is zero, and the vector sum of the currents in the three wires is also zero. In the practical three-phase circuit such is not the case. The vector sum of the voltages to ground of the phase wires is never quite zero, and the vector sum of the currents in the three wires is not zero. In inductive coordination studies it is customary to divide the voltages to ground and the currents into "balanced" and "residual" components.

The balanced voltages are those components of voltage to ground which are equal in value and so related in phase that their vector sum is zero.

The residual voltage is the vector sum of the voltages to ground of the phase wires. It is equivalent to a single-phase voltage impressed between the three wires in multiple and ground.

The balanced currents are those components of the currents in the wires whose vector sum is zero. They are confined to the wires of the circuit and their algebraic sum from instant to instant is also zero.

The residual current is the vector sum of the currents in the three phase wires. It is equivalent to a single-phase current in a circuit consisting of the three wires in multiple as one conductor and ground as the other.

In recent terminology the balanced components are those of positive and of reverse phase sequence, the residual being a zero-phase sequence component.

The effects of balanced voltages and currents can be neutralized to a large extent by the use of suitably coordinated transpositions in the power and telephone circuits. The effects of residual voltages and currents are cumulative along an exposure, bringing the potential of the telephone line and equipment to a relatively high value above ground. Induction from these components obviously is not affected by transpositions in the power circuit.

GENERATOR WAVE FORM

The type of wave of voltage striven for in the design of a-c. generators is the pure sine wave. This is impossible of exact attainment, but a very close approximation is reached in modern designs. In the Standardization Rules of the Institute a limit is set for the Deviation Factor, a measure of the deviation of the actual open-circuit terminal voltage wave of a synchronous machine from a pure sine wave.

Actually certain harmonics are present in the generator wave in varying amounts. If the positive lobe of the wave is identical with the negative lobe, only odd harmonics are present. The tendency is for the higher harmonics to be damped out in the impedance or magnified slightly in the capacitance of the circuit to which the generator is connected. At times certain harmonics are carried through one or two transformations and can be detected from their inductive effects on paralleling communication circuits.

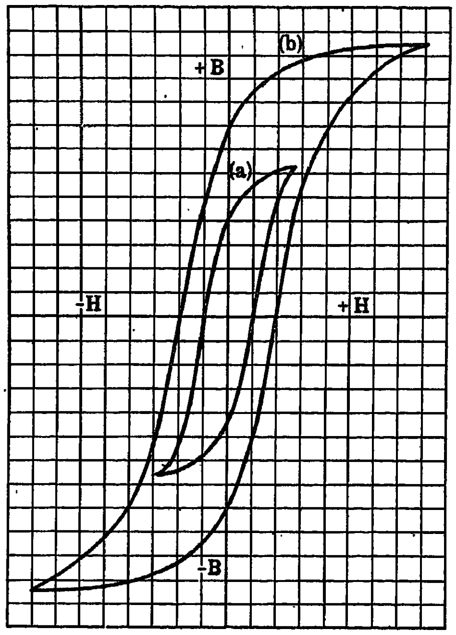

FIG. 1—MAGNETIZATION AND HYSTERESIS CURVES AT DIFFERENT STATES OF SATURATION

TRANSFORMER EXCITING CURRENT

The chief cause of higher harmonics in a power system is the exciting current of the transformers. Even if the generator wave is a pure sine wave of voltage, the

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Presented at the Pacific Coast Convention of the A. I. E. E., Spokane, Wash., Aug. 28-30, 1928.

exciting current demanded by the transformers will contain higher harmonics superposed on the fundamental wave if the circuit will permit their flow. If it will not, the deficiency shows up as higher harmonics in the voltage wave.

To recall the relations existing, Fig. 1 is presented showing the magnetization and hysteresis curve, Fig. 2 showing the peaked exciting current required by a sine wave of voltage, and Fig. 3 showing the resulting wave of flux if the current is compelled to follow a sine wave, as for example in a current transformer with open circuited secondary coil.

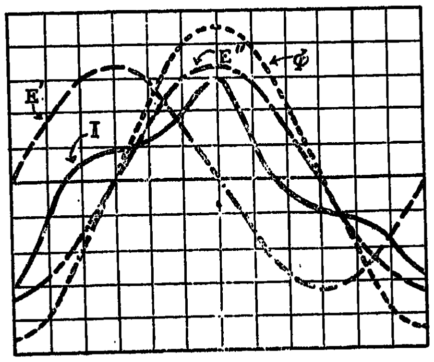


Fig. 2—Sine Wave of Voltage, Peaked Wave of Magnetizing Current

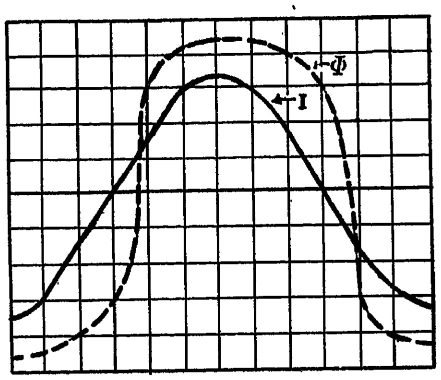


Fig. 3—Sine Wave of Current, Flat Wave of Flux

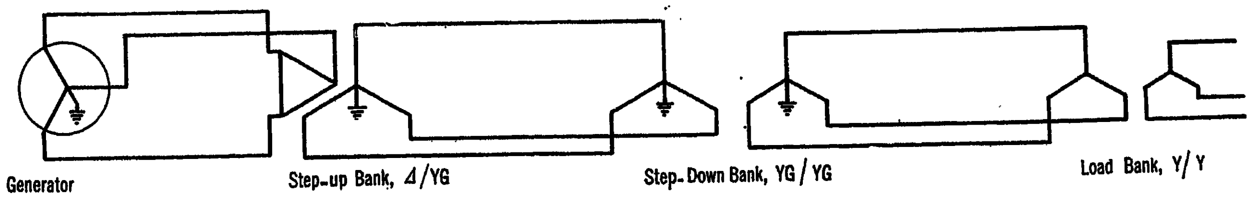


Fig. 4—System Supplied from One Generator

If a single-phase transformer is connected to an a-c. source, the resulting exciting current is as shown in Fig. 2. If the iron of the transformer is worked at low density, the hysteresis curve being of the form indicated in Fig. 1A, the distortion of the current wave will be slight. If worked at high density, the hysteresis curve being of the form shown in Fig. 1B, the current wave will be considerably distorted. Note that the distorted wave of current *is necessary* in order to produce a sine wave of counter e. m. f. to oppose that applied, and that consequently the secondary e. m. f. wave is also a pure sine wave.

The exciting current of the single-phase transformer contains a pronounced third harmonic, an appreciable fifth, and higher harmonics in varying amounts. Working the iron at high saturation increases the magnitude of the harmonics, bringing out also some of the higher ones which are not noticeable at low densities.

TRANSFORMER CONNECTIONS

When transformers are connected in banks on a three-phase system, certain connections permit the flow of harmonic currents and others do not. It is not intended here to repeat analyses of a large number of possible combinations, but to emphasize the relations existing on a few of the types commonly used. An elemental system supplied from one generator is shown in Fig. 4.

GENERATOR

Present practise favors the Y connection for three-phase generators, with neutral grounded, either solidly or through a resistance. This limits the insulation strain on the windings definitely to the Y voltage. It is somewhat easier to obtain a good wave form with this than with the delta connection.

STEP-UP TRANSFORMERS

Practise also favors the delta connection for the primary of the step-up transformer bank. In this connection, a sine wave of voltage between conductors will result in a peaked wave of magnetizing current, the necessary third harmonic currents being in phase in each transformer and thus circling around in the closed delta with very low impedance. The secondary voltage will then be free of third harmonic components.

If other harmonics than the fundamental are present in the wave of applied voltage, the same considerations as noted regarding the third harmonic current apply to the third multiples of the other harmonics, such as the 9th, 15th, 21st, 27th, 33rd, etc., which will be represented in the delta current, as these will be required in the magnetizing current in order that the 3rd, 5th, 7th, 9th, 11th, etc., components of the primary voltage may be passed on faithfully to the secondary side.

The secondary or line side of the step-up transformer bank is usually connected Y with grounded neutral. As in the case of the generator, this adds to safety and reliability of operation by limiting the voltage from line to ground definitely to the Y voltage. Thus far on our typical system we have on the line a good wave form of voltage if we started with a good one at the generator.

STEP-DOWN TRANSFORMERS

Again practise favors the Y-grounded connection for the line side of the step-down bank, in this case the primary side. With practically a sine wave of voltage applied, these transformers demand the harmonics required in the magnetizing current in order to produce the same type of voltage wave. Each transformer therefore will draw from the line, if the connections permit, current of 3rd, 5th, 7th, 9th, 11th, etc. harmonics of the fundamental frequency.

Taking the 3rd harmonic as of major importance in this analysis, it will be recalled that in a three-phase system the third-harmonic components, either of voltage or current, will be 3 times 120 or 360 deg. apart—in other words, in phase with each other. With the ground connection on the neutrals of both step-down and step-up banks, a path is provided for these in-phase components of the magnetizing current. The third-harmonic currents demanded in each leg of the step-down bank cannot pass out to the line through the other two legs of the Y, but they can pass through the neutral connection and ground to the neutral of the step-up bank, and through the Y-connected secondary windings of that bank to the line, thus finding a closed path. The delta-connected primary windings of the step-up bank allow rather free circulation of any third harmonic currents necessary to offset those demanded by the step-down bank. The "triples" thus find in that bank a low-impedance portion of their path, the rest of it consisting of the loop formed by the three conductors in parallel and the ground, and the bank demanding them.

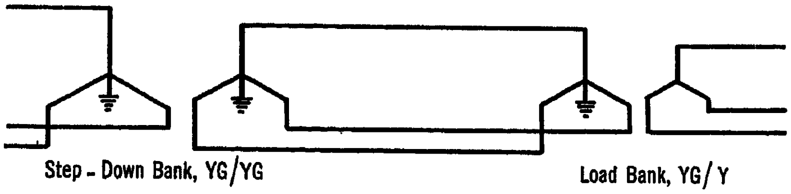


Fig. 5—Load Bank Connected *YG/Y* (Primary, Y-Grounded, Secondary, *Y* with Isolated Neutral)

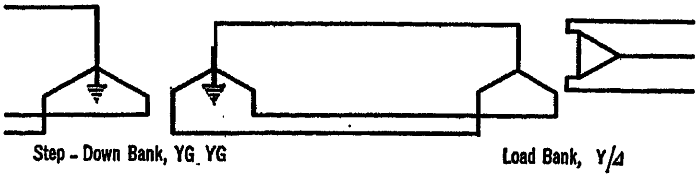


Fig. 6—Load Bank Connected *Y*/Δ (Primary, *Y* with Isolated Neutral, Secondary, Delta)

The third-harmonic currents thus form the chief portion of the residual current. Other important components are the 9th, 15th, 21st, etc. harmonics, if the 3rd, 5th, and 7th harmonics were present in the voltage wave. The term "triples" applies to all such components.

Those harmonics of exciting current whose designating number is not divisible by 3, such as the 5th, 7th, 11th, 13th, etc., are supplied over the line, and like the fundamental, the resultant for each is zero. They, with the fundamental, form the balanced components of the current.

Practically, the voltage wave is not of perfect sine form; transformers are not always exactly alike; load is not always balanced; unequal leakage from the conductors to ground takes place; the capacitances from conductors to ground are not always equal; all of these factors contribute to add small amounts of fundamental and other odd harmonics to the residual current, but those mentioned, the 3rd, 9th, 15th, etc., predominate.

LOAD BANK

The load bank in Fig. 4 is represented as connected Y-Y with isolated neutral. In this type of connection, the triple-harmonic currents demanded by the exciting current of the transformers cannot flow as no path is provided for them. The deficiency of third harmonic in the magnetizing current appears as a third harmonic in the secondary voltage and distortion of the applied voltage wave. The same is true of the other harmonics which seek the neutral path,—the 9th, 15th, 21st, etc. As in the case of the currents, these harmonics combine into a residual voltage by which the isolated neutral differs from ground potential. This difference is superposed upon the various phase-wire voltages from ground, and there results a residual electrostatic field in the medium surrounding the conductor which varies with the frequency and resultant magnitude of these harmonics.

As in the case of the currents, those harmonics of voltage whose designating numbers are not divisible by three,—such as the 5th, 7th, 11th, 13th, etc., appear on the different conductors, but their resultants are each zero.

If the load bank is connected Y–Y with the primary neutral grounded as in Fig. 5, the third-harmonic currents required for magnetization can come only from the step-down bank, through the conductors and ground return. In order to supply them, the step-down bank must draw upon the step-up bank with its delta-connected primary. Thus the load bank increases the residual current in the line back to the source which can furnish them.

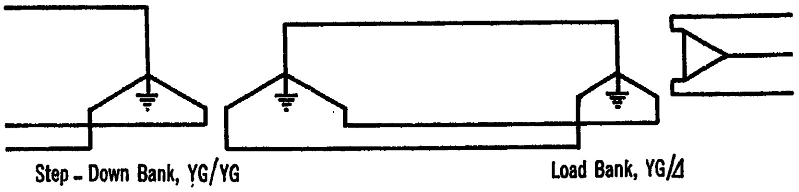


Fig. 7—Load Bank Connected YG/Δ (Primary, Y-Grounded, Secondary, Delta)

If the secondary of the load bank is connected delta and the ground on the primary neutral is removed as shown in Fig. 6, no third-harmonic currents can flow in the primary, so the secondary voltage wave and the primary wave of back e. m. f. tend to become distorted. However, at the slightest appearance of a third-harmonic in the delta voltage, a third-harmonic current flows in the closed delta and supplies the deficiency in magnetization, so the voltage waves remain smooth except for the small amount of triple harmonic necessary to overcome the triple-harmonic impedance.

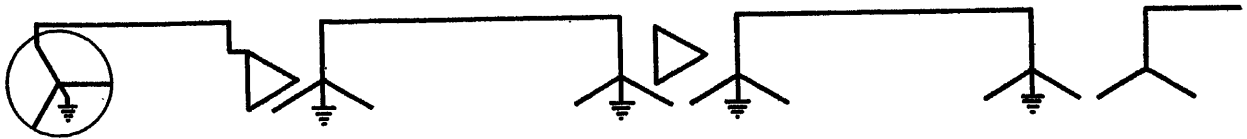


Fig. 8—System Supplied from One Generator, Tertiary Delta in Step-Down Bank

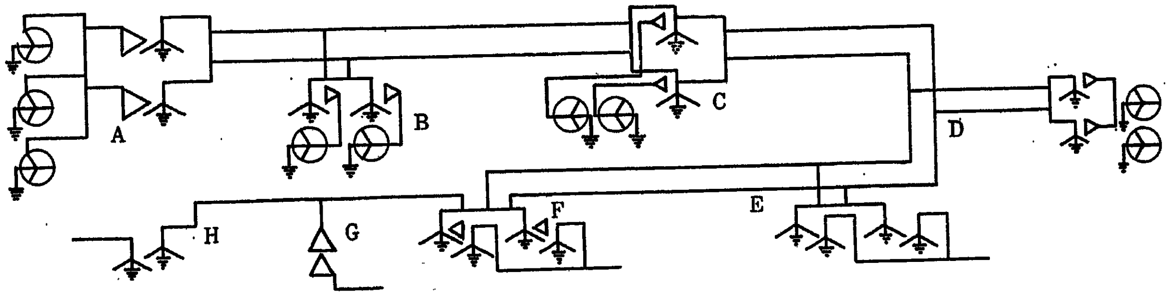


Fig. 9—Typical System Network

If the primary neutral is grounded, the secondary being delta-connected as shown in Fig. 7, nearly all the third-harmonic magnetizing current will be supplied by the secondary delta. Some, however, will be supplied to the primary over the line from the source through the step-down bank. The relative amount of third-harmonic current supplied by the secondary delta and the line will depend upon their relative impedances. The delta secondary path will, in general, have a very low impedance compared to the line path, so there will be very little residual current in or voltage on the line between the load bank and the step-down bank.

Tertiary Windings

If separate windings are added to the transformers of the step-down bank and connected delta, most of the triple-harmonic currents required for the excitation of that bank and of the load bank will be supplied in the delta circulating current, so the line back to the step-up bank, (see Fig. 8) will be comparatively free of residual current. The division will depend upon the relative impedance. If the delta is of large kv-a. capacity with low impedance it will be more effective in this regard than if of small kv-a. capacity with high impedance, and as will be shown later, it may even be too large to be of maximum benefit.

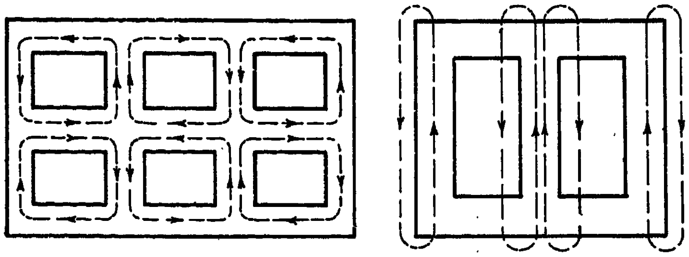
Power Networks

The usual power system is not so simple as the elemental one depicted in Figs. 4 to 8. Most systems have more than one power station, with more than one generator and transformer bank at each, feeding the system at different points and into multiple lines. When some of the transformers are connected Y-grounded on both sides, some with tertiary-delta windings, some Y-delta, some delta-delta or delta-Y, it is rather difficult to trace out fully the course of the residual currents, which is further complicated by variations due to system changes.

However, by analyzing the conditions from the fundamental principles just treated, at least the general features of any problem can be determined, and reasons deduced for any particular conditions encountered.

In Fig. 9 a more complex condition is presented. *A* and *B* are power plants not far apart feeding into twin transmission lines. At *C* is a station with step-down auto-transformer banks with delta-tertiary windings which are connected to synchronous condensers. Another power plant feeds in at *D*, and at *E*, *F*, *G*, and *H* are step-down stations serving communities and industries.

The delta-Y connected plants deliver a good wave form of voltage to the line. The Y-connected auto-transformers at *C*, if the tertiary delta is of low enough impedance, will furnish practically all the triple harmonics needed by those banks whether the condensers are on or not. The Y-Y grounded banks at *E* will require triples for their magnetizing current. They will draw them from the banks with deltas in them, at *D* and *C*, the relative amounts depending on the impedance of the paths to these sources. The banks at *F* with delta tertiaries will supply practically all their own triples unless the tertiary impedance is high, in which case part of them will be furnished from *D* and *C* also.



(a) Shell Type (a) Core Type

FIG. 10—MAGNETIC CIRCUITS OF THREE-PHASE TRANSFORMERS

The bank at *G*, being delta-connected on the primary, will not affect the situation regarding triples at all. The bank at *H*, connected Y-Y with grounded neutrals, will require triple harmonics of current. The bank at *G* cannot supply them, so they must come from *F* and possibly some must come from *D* and *C*.

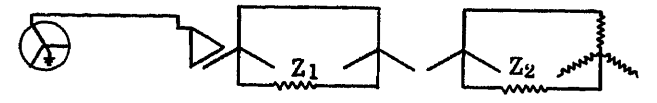


FIG. 11—CONNECTIONS FOR TEST OF TRIPLE HARMONIC CURRENTS TO LOAD

If a power network is well supplied with banks having delta windings, the residual currents are reduced to low values. The most effective means for their suppression is to have the delta in the bank itself either as a delta connection on primary or secondary, or as a tertiary winding if it is a Y-Y bank. At a station where there is a number of banks, the use of such windings in one or two of the banks will serve for all practical purposes,—while the banks so equipped are in service.

SUPPLEMENTARY Y-DELTA BANKS FOR SUPPRESSING RESIDUALS

Some engineers have preferred to install supplementary banks of relatively small transformers connected Y-grounded on the primary and delta on the secondary side, where suppression of residual currents and voltages was required. Such a bank will do its share of the task of furnishing triple-harmonic components of magnetizing current, its effectiveness being in inverse ratio to its impedance compared to other available paths. In the individual case, the effectiveness desired and the comparative cost of the separate bank and the addition of tertiary windings on the main bank, including installation, will govern.

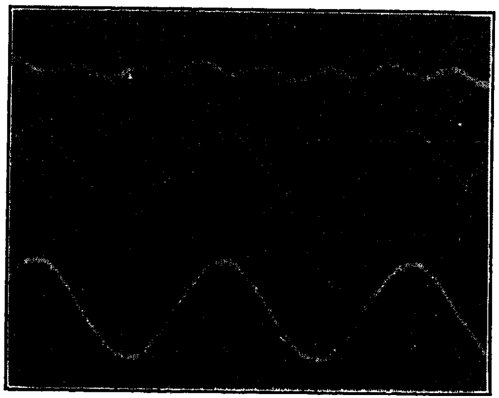


FIG. 12—NEUTRAL CURRENT THROUGH PURE-RESISTANCE LOAD WHEN VOLTAGE WAVE DISTORTED.

Top curve is neutral current, 0.068 amperes. Middle: Y-voltage at load, 106 volts. Bottom: Load current, 1.67 amperes

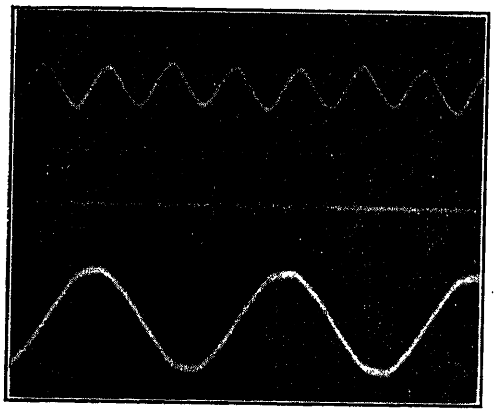


FIG. 13—PRIMARY NEUTRAL ISOLATED. HARMONICS SUPPLIED THROUGH NON-INDUCTIVE LOAD AND SECONDARY NEUTRAL

Top curve is current in neutral from load, 0.205 amperes. Middle: Current in primary neutral 0 ampere (open). Bottom: Line voltage, 110 volts.

THREE-PHASE TRANSFORMERS

A discussion of residual currents and voltages would not be complete without mention of three-phase transformers. The shell type is quite similar in its characteristics to three separate transformers. In standard designs the middle phase is reversed in order to reduce the area of the iron magnetic circuit necessary between phases. Thus there is an independent magnetic circuit for each phase, and the triple-harmonic fluxes have short and low-reluctance paths as shown in Fig. 10A. If the primary or secondary windings are connected delta they will furnish them, or if Y–Y with tertiary delta, part or all of the triple-harmonic fluxes required will be furnished by currents in the delta.

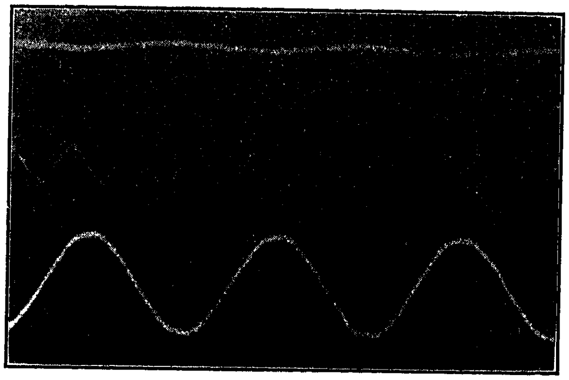


Fig. 14—Primary Neutral Closed. Fundamental Only in Load Neutral

Top curve is current in neutral from load, 0.007 ampere. Middle: Current in primary neutral, 0.2 ampere. Bottom: Line voltage, 110 volts

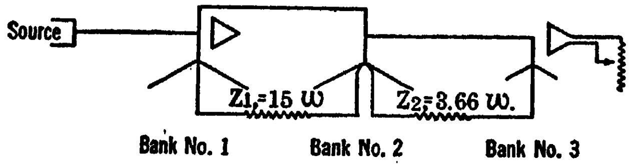


Fig. 15—Connections for Regulation of Residual Currents

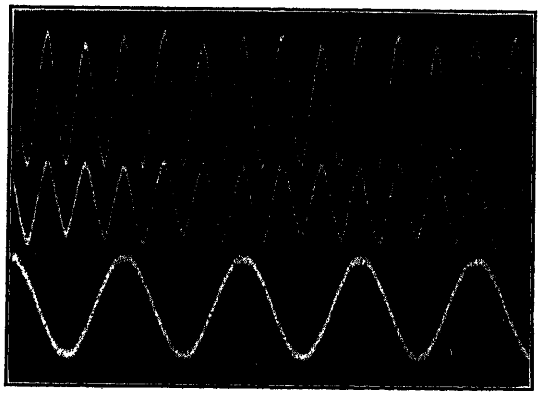


Fig. 16—Neutral Currents with Delta Open

Top curve is neutral current, bank No. 2 to bank No. 3. Middle, neutral current, bank No. 1 to bank No. 2. Bottom, line voltage, 220 volts

In the core type the magnetic flux of any one phase has its return path through that of the other two phases, so for the balanced components the resultant of the fluxes must be zero. However, any triple-harmonic fluxes due to the absence of triple-harmonic magnetizing currents are simultaneously in the same direction in each leg as shown by the arrows, Fig. 10B, so the magnetic circuit for them can be completed only through high-reluctance leakage paths through the air or case.

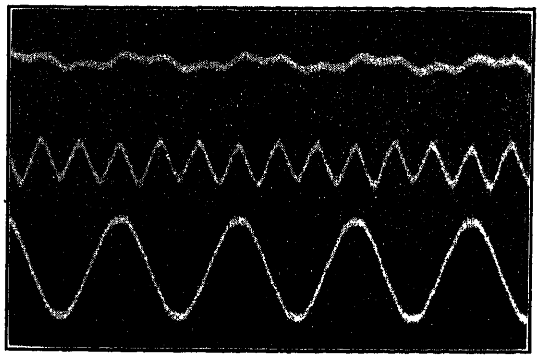


Fig. 17—Neutral Currents with Delta Closed Through Resistance

Top curve is neutral current, bank No. 2 to bank No. 3. Middle: Neutral current, bank No. 1 to bank No. 2. Bottom: Line voltage, 220 volts

Laboratory Tests

In order to check some of the features outlined regarding banks of single-phase transformers, an interesting series of experiments was conducted in the laboratory of the Pacific Gas and Electric Company at Emeryville, Calif., with three banks of 1-kw. transformers, using the 110-volt windings as primary and secondary and taping up the 2300-volt terminals, except that in some of the experiments the 2300-volt windings of one bank were used as a closed delta. By confining attention to the exciting currents the relative values of the harmonic currents were appreciably large. A number of conclusions was determined by the tests, which substantiated the theory presented.

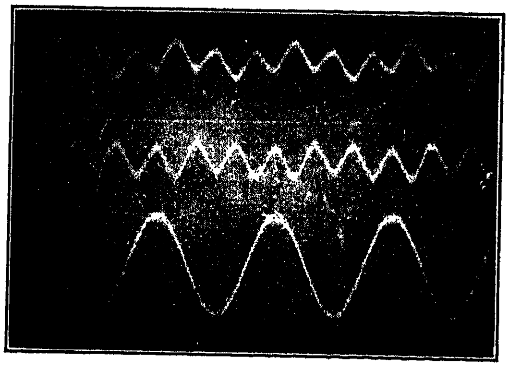


Fig. 18—Neutral Currents with Delta Closed Solid. Phase of Residual Current, Bank No. 2 to Bank No. 3 Reversed

Top curve is neutral current, bank No. 2 to bank No. 3. Middle. Neutral current, bank No. 1 to bank No. 2. Bottom: Line voltage, 220 volts

A Y–Y grounded bank will not send out triple-harmonic currents on the secondary side to pure-resistance loads if there is free circulation of the triple harmonics required on the primary side for excitation. If the latter are suppressed, causing triple harmonics of voltage on the secondary side, there will be triple-frequency components in the load current.

The connections for this test were as shown in Fig. 11. Bank No. 1 was connected delta-Y in order to eliminate any triple harmonics of the generator. The load consisted of a 200-watt lamp in each phase. Small air-core impedances were placed in the connections between neutrals to represent line impedance for the residual currents. With large values of impedance the wave of secondary voltage was distorted and a triple-harmonic current flowed in the neutral conductor between the load and the transformer bank serving it as shown in Fig. 12.

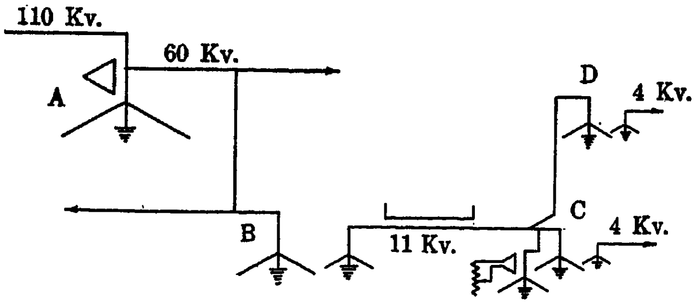


Fig. 19—Residual Currents Suppressed by Supplementary Bank

Still clearer results were obtained when the neutral was opened between banks and Z_2 reduced to zero by omitting the coil in the neutral between load and bank. In this case the triple harmonics demanded by the Y–Y bank were supplied through the secondary side and the load, as shown by the oscillogram of Fig. 13.

When the primary neutral of the Y–Y bank was closed through, (Z_1 and Z_2 both zero), the free flow of triple-harmonic currents was permitted on the primary side and the neutral from load to bank contained only fundamental-frequency current as shown in the oscillogram of Fig. 14.

Another matter determined was the action of a delta secondary (or tertiary) winding, in supplying a part only, all required, or an excess of triple-harmonic current over that required in the same bank. The connections for this test were as shown in Fig. 15, the transformers in the first two banks in this case being connected as auto-transformers, the delta in the first bank consisting of the 2300-volt windings.

With the delta of bank No. 3 completely open, the oscillograph was set so that one wave of each of the neutral currents and the 60-cycle line voltage were in phase as shown in Fig. 16.

By adjusting the resistance in the delta it was possible to reduce the neutral current to practically a fundamental-frequency wave. Owing to the impossibility of observing visually and taking an exposure at the same time with one oscillograph, Fig. 17 shows the neutral current between No. 2 and No. 3 banks with some triple-harmonic current superposed on a small fundamental-frequency wave, and the triple harmonics in the two neutrals are still in phase, *i. e.*, there are still triple-harmonic currents flowing from bank No. 2 to bank No. 3.

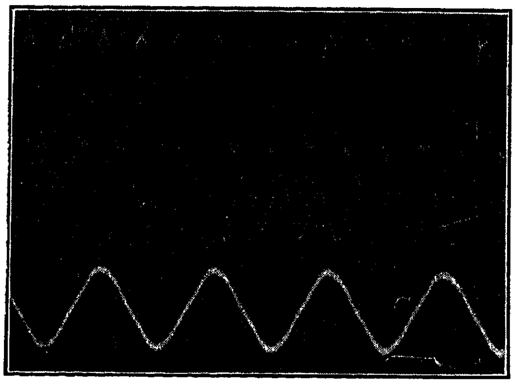


Fig. 20—Residual Current on Line. Delta of Supplementary Bank Open

Top curve is delta voltage. Middle: Residual current on line. Bottom; Reference or timing wave, 104 volts

When the delta was closed completely, it not only supplied all the triple-harmonic current required by its own bank but aided in filling the demands of bank No. 2. This can be noted from Fig. 18, where it will be seen that the residual current has completely reversed in phase between the second and third banks.

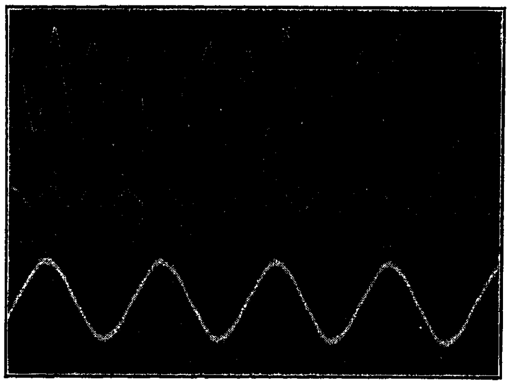


Fig. 21—Residual Current on Line, Delta of Supplementary Bank Closed

Top curve is delta current. Middle: Residual current on line. Bottom: Reference or timing wave, 104 volts

Field Tests

A very similar arrangement was set up in the field at a substation connected to a line which had given trouble from residual currents. The conditions were as indicated in Fig. 19. An auto-transformer bank at A contained a delta but at B the voltage was stepped down from 60,000 to 11,000 volts through a Y-Y bank with neutrals grounded. The 11,000-volt line supplies two stations also equipped with Y-Y banks transforming from 11,000 to 4,000 volts. A parallel existed between B and C on the 11,000-volt line.

A supplementary bank of about 25 per cent of the capacity of those at C or D was installed at C, connected Y-grounded on the primary, and delta on the secondary side, with an adjustable resistance across one corner of the delta. With the delta open the triple-harmonic currents were supplied from A through bank B for the banks at C and D. It was possible to vary the resistance till the residual current in the line was approximately all fundamental, but due to system variations and lack of facilities to observe and make the exposure at the same time, no oscillogram of this condition was obtained. Figs. 20 and 21, however, show the neutral current with delta completely open and completely closed, compared with the same timing wave. A complete reversal can be noted, indicating that the supplementary bank, when the delta was closed, supplied the triple-harmonic currents required by its own primary windings, by the large bank at C and by the bank at D, and a portion of those required by the bank at B. This corresponds to the results obtained in the laboratory on the somewhat similar set-up shown in Fig. 15, in which the conditions were more easily controlled.

CONCLUSION

It appears evident that attention to fundamental principles of the electric circuit will enable the engineer to determine in general the course of residual currents in any given transmission system or network. Higher harmonics of currents are required in transformer magnetizing current, the suppression of which will give rise to higher harmonics of voltage. The higher harmonics follow definitely the ordinary law of alternating currents, namely, $I = E \div Z$, in each case.

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Discussion

N. C. Clark: I wonder if Mr. Corbett would tell us if he has done anything on higher harmonics. I know from oscillographic studies at the University of California that there is quite a large fifth harmonic introduced by the iron in transformers, sometimes amounting to as much as 40 per cent of the third. Of course the relations of three-phase circuits do not at present yield any obvious method of connection to neutralize or choke the fifth and seventh harmonics, but perhaps Mr. Corbett has done something on this or could suggest some method of suppressing them.

A. W. Copley: The test results indicated by Mr. Corbett for the circuits shown in Figs. 15 and 19 are of considerable interest from a practical standpoint. It has been generally accepted as good practise for star-star transformer banks to be equipped with a delta winding for the purpose of supplying the triple harmonics of magnetizing current required by the banks. There are, however, many transformer banks in service which are not provided with such a delta winding. When these banks have a grounded neutral the triple-harmonic current is obtained from other transformer banks which are connected star-delta. As the banks with the delta may be at a considerable distance from the star-star banks, the triple harmonic flows for a long distance in the ground and therefore gives rise to telephone interference.

Judging from Mr. Corbett's paper, the particular location of the star-delta bank supplying the triple harmonic seems to be quite important. Moreover, the impedance of the delta winding is also quite as important as the location of the bank. It is implied that, by properly proportioning the impedance of the delta winding and properly locating the star-delta bank, it is possible to reduce to a very considerable extent the magnitude of the triple harmonics which might flow in the ground at any particular location. The application of this idea can undoubtedly be successfully used in the prevention of the flow of triple harmonics along certain specific parallels. It is not, however, a general solution of inductive interference troubles from triple-harmonic currents.

D. I. Cone: Mr. Corbett has mentioned transformers and generators as causes of harmonics in power systems. A third important source is the electric arc, as in mercury-arc rectifiers.

To illustrate the importance of the factor of transformer saturation, it may be noted that a change of 1 per cent in the voltage on a transformer, as commonly rated, produces a change of from 5 to 15 per cent in the exciting-current harmonics. Thus a few per cent change in the voltage applied to the transformer has been observed to increase or decrease these harmonic currents by as much as one-half. In investigating a case of induction trouble, which increased at times of light load, it was found that the transformers responsible were being energized at a higher voltage at light load with corresponding increase of the triple harmonic residuals.

Under "Step-up Transformers" it is stated that the secondary voltage will be "free" of third-harmonic components where deltas of low impedance are provided. As a matter of practise, it is found that the star-star transformers give the maximum triples, while a low-impedance delta connection may reduce them to as little as 5 to 10 per cent. A technique was developed some years ago in connection with the California studies to which Mr. Corbett referred, by which approximate values can be estimated for the amounts of these triple harmonics. In studies that have been made, even on complicated systems of the kind shown in Fig. 9, a fair agreement between preliminary estimates and actual test results has resulted.

This method is described by Osborne in a discussion, (see page 2175, TRANS. A. I. E. E., Vol. 34, 1915). Each transformer, as far as the exciting-current harmonics are concerned, is treated as an impedance in series with a generator, and with appropriate representation of leakage and line impedances.

The use of supplementary banks to absorb the triple harmonics of star-star banks has been explored considerably. In one case of a star-star bank with both neutrals grounded, and an exposure adjacent, the proposal was made to provide an auxiliary Y-delta bank to be connected in this way. The proposed bank was small, (about 20 per cent or less of the capacity of the Y-Y bank). However, it was pointed out that, having the Y-delta bank at the same station with the Y-Y bank, it was practicable to connect the neutrals of the two banks together, but isolated from ground. This procedure provided for the triples of the Y-Y bank and opened the circuit for triple harmonics along the exposure.

The proposal indicated in Fig. 19 of the paper, for controlling the triple-harmonic residuals in a particular exposure between

B and *C*, by means of a delta with resistance, has the effect of increasing the residual voltage and of causing increased flow of triple-harmonic residuals in other parts of the network. Such a scheme must be applied with caution to the particular case, because in improving one part, difficulty may be caused elsewhere. Observations of the induction also indicate that the adjustment is rather unstable so that variations of voltage and of switching arrangements in adjacent lines tend to upset the balance and increase the residual current.

R. E. Kistler: In Mr. Corbett's paper he has emphasized the importance of having the step-up banks connected delta-star. If they were connected star-star and grounded, the odd triple harmonics from the generator would circulate freely and would produce high inductive effects. Where, however, there are intermediate sections of transmission network connected directly to the generators having their neutral grounded, the capacitance to ground of the feeder network, arising either from long open-wire sections or cable sections, may provide sufficiently low impedance to permit the flow of enough residual current, due to the impressed residuals from the generators, to cause interference. In some such cases residual current or prominent harmonics thereof have been limited by the installation of the resistors or reactors or anti-resonant shunts in the generator neutral. In other cases, consideration has been given to the use of special design features in new generators to limit the triple harmonics in the phase-to-neutral voltage wave.

The oscillograms shown in Mr. Corbett's paper relative to the effects produced on the triples in the various portions of the setups shown on Figs. 15 and 19 clearly indicate the benefits to be derived by the use of star-delta banks. The results also show the importance of locating such star-delta banks properly so as to provide for reduction of the odd triples in the desired sections of the power network. The use of resistance in the delta winding of such banks is equivalent to the insertion of resistance in the neutral-to-ground connection on the primary side in so far as limiting the residual currents taken from the line by this transformer bank is concerned, with the exception that its own odd triple magnetizing currents, with the delta resistor, would of necessity then be supplied from the line in correspondingly increased proportions.

Roy Wilkins: I should like to point out in Mr. Corbett's paper a couple of the practical objections the operating engineer will meet when he applies such a system to residual-current correction.

Until 1910 exciting current on the average power transformer ran from 8 to 10 per cent. Some of the older ones that are still in service, of the older Stanley make that were built twenty years ago, run even higher than that at normal voltage. Unfortunately, those transformers are run many times at more than a normal saturation. They are, of course, the worst offenders toward putting out odd harmonics on the line.

The present transformers as manufactured run as low as 2 per cent of the full-load current. There have been cases in the last two or three years where banks as large as 50,000-kv-a. had less than 2 per cent. One case that I know of measured current at normal voltage of 1.4 per cent exciting current of the normal full-load current.

As you run up on the knee of the saturation curve, the percentage of exciting current increase for rise in voltage, and on many transformers a 10 per cent increase in voltage will increase the exciting current 100 per cent.

As you go up in exciting current, you also go up in the effect of the higher harmonics. If you get a heavy exciting current the effects of the seventeenth and twenty-first harmonics become apparent, and those harmonics are particularly detrimental for communication circuit. That was one point.

The second is that in applying a Y-delta bank, provision must always be made for transient troubles on the system. Whenever a Y-delta bank is put on a grounded system, the delta must be big enough to protect the bank itself. In other words, with one grounded phase that delta must be able to pass enough current to relay out the high-tension side.

One obvious method of correcting this is to open the delta, and in all cases that I know of where that has been tried, disastrous results were encountered. If you relay the delta open in a case of trouble on the high-tension side, you give rise to voltages in the transformer which probably will puncture the insulation.

One other thing it is well to keep in mind is that in all of these circuit connections we do not dispense with the harmonics of the primary wave. In other words, you only change from current to voltage or vice versa; connecting a bank up in a certain way does not eliminate the exciting current. It simply converts it from current to voltage. It then becomes a problem of deciding which is the most detrimental use for the bank to be put to.

J. O'R. Coleman: (communicated after adjournment) In this paper two very important points are brought out, which if given proper consideration in the planning of electrical supply could be taken care of with little or no inconvenience or expense. However, if these points are not properly considered initially the coordination problem may be difficult and expensive.

The transformer requires certain harmonics in the exciting current even though the impressed voltage is a sine wave. Fortunately, these harmonics are usually not excessive in transformers of good design operated at rated voltage. However, in order to obtain economy in construction the core is designed to operate at a high flux density, and as shown by Fig. 1 in the paper a relatively small increase in the flux density above the design value caused by increased impressed voltage above normal required a considerable increase in magnetizing force. This increase in magnetizing force results in a large increase in harmonics in the exciting current. Therefore, a relatively few large transformers on a system operating above normal voltage can materially increase the inductive influence of a whole system.

The paper not only shows how delta-connected windings can be used to limit the transmission of triple-harmonic exciting current over the lines but shows how and why the use of delta-connected windings may exaggerate the conditions that they are supposed to remedy.

A proper consideration of these two apparently small factors in both transmission and distribution will materially aid in the solution of a rather difficult and trying problem.

L. J. Corbett: Possibly if Mr. Clark had read the paper a little more thoroughly he would have noted my mention of the fifth and seventh harmonics. Those which are not triples are balanced exactly the same as the fundamental. The resultant of each becomes zero in any three-phase line. The residual is not absolutely free of them, however, because the value of the residual current is also influenced by leakage of insulators, by the difference in capacitance to ground of the conductors, and by things of that sort, which do bring in a little of the fifth and seventh and other odd harmonics, just as they do the fundamental. There is always some fundamental in the residual current. Because of the influence of the Y-Y and Y-delta banks on the triple harmonics, they were given the most attention in the paper.

I am glad Mr. Copley emphasized the point that it is not always best to have a delta in a transformer bank. Sometimes you have too much delta for your conditions, and you may get stray residual currents from other directions. It is, as has been pointed out by others, a matter for very careful consideration of every case.

Mr. Cone believes that the Y-Y banks are the worst offenders. I agree. He said further that the harmonics are reduced if the delta is present, but he never saw the delta which reduced them to zero. I think the answer to that is in the reversals shown in the paper. There is a certain point at which the residual currents on the lines are reduced to zero, but due to changing system conditions they may flow back and forth. At a given instant for a certain setting they are zero. Then the slightest rise in voltage on the system throws them in one direction; the slightest lowering of voltage sends them in the other direction. This is due to the changing requirements for magnetization.

Mr. Cone referred to Mr. Osborne's discussion and to his method which is common among our telephone friends, in which these banks are called generators of residuals. To my mind. calling Y-Y bank a generator of residuals is like calling a hungry man a generator of a chicken dinner. It is a void; it is a vacancy; it is a suction which pulls these residual currents into the Y-Y bank. To consider such banks sources of residual currents seems to me a misnomer. This may be only a difference of language but it seems a real difference in thought, to the extent of 180 deg., as mentioned by Mr. Cone. Mr. Osborne's method is no doubt useful mathematically for certain purposes, but in this paper the endeavor was to present the physical facts.

Mr. Kistler stated that he would prefer to see the resistance inserted in the Y-ground rather than in the delta. I think there is a difference, because when a resistance is placed in the ground connection of the Y, there is an increase in triple-harmonic voltage as well as a reduction in triple-harmonic current. In using a delta you actually furnish some of the triple-harmonic current required for magnetizing, and you lessen the triple-harmonic voltage.

I was glad to have Mr. Wilkins call attention to the differences in values of harmonics with magnetization which were not fully emphasized in the paper. If we had run the saturation higher in our laboratory tests we would have introduced much higher values of harmonics and would have had a very much more distorted wave. I refer anyone interested to Mr. Frank's[1] excellent paper before the Institute in 1910. He used a number of transformers, singly and in banks, and took a number of oscillograph curves. He increased the excitation to as high as 200 per cent, which gave an extremely peaked wave of current, and brought in very large values of harmonics far up in the range.

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[1] John J. Frank, *Observation of Harmonics in Current and in Voltage Wave Shapes of Transformers*, A. I. E. E. TRANS., Vol. XXIX, 1910, p. 809.

Power-Line Carrier Telephony

BY L. F. FULLER[1] and W. A. TOLSON[1]
Fellow, A. I. E. E. Non-member

Synopsis.*—The inherent advantages of carrier-current telephony over high-voltage power transmission lines during the past five years have resulted in an unusually rapid development of this form of communication. To one who has not been constantly in touch with this rapid development, the necessity for the numerous types of carrier-current telephone equipment now available is not always apparent. This paper gives a brief outline of modern communication requirements in this field, the problems involved in providing this communication, and a brief outline of the different types of equipment now available to provide the required communication.*

COMMUNICATION requirements may be classified according to their complexities as follows:

1. Requirements which may be fulfilled by the use of a single channel. A system meeting these requirements is analogous to a single telephone line connecting all stations on the system. The practical limit to which such a system may be extended is determined by the volume of traffic handled.

2. Requirements making necessary the use of several communication channels on the same transmission lines, to handle more traffic than can be satisfactorily cared for by a single channel.

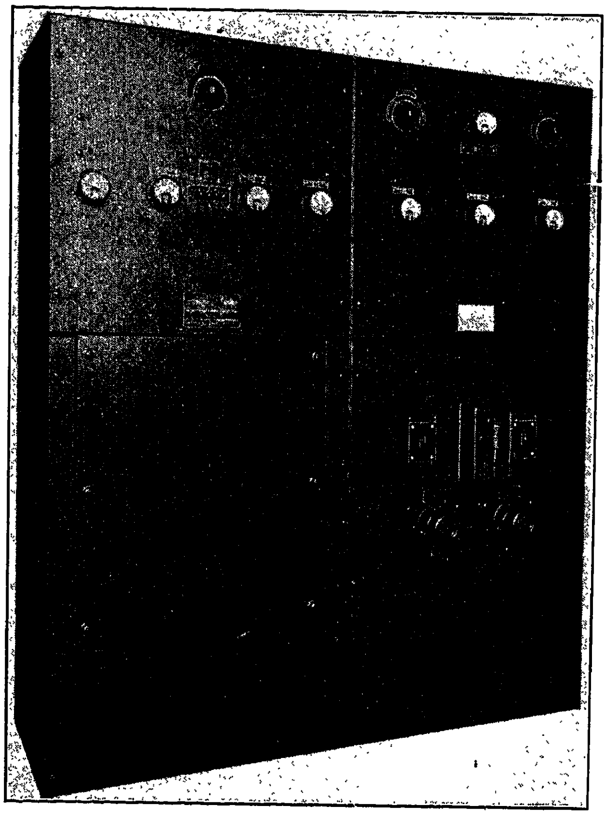

FIG. 1—TRUNK-LINE CARRIER-CURRENT TELEPHONE TRANSMITTER—RECEIVER UNIT

3. Requirements making it advantageous to employ long "trunk" channels, each trunk station collecting traffic locally by private line extensions, or by secondary carrier channels from points not on the trunk channel.

4. Communication is often required between trunk or secondary carrier stations and isolated points, such as (a) patrolman's houses near the transmission line, (b) open air stations permanently located at isolated switching points, and (c) designated points for use of portable equipment.

In providing equipment to meet the communication requirements just outlined, many problems present themselves in connection with the operating requirements and the electrical characteristics of the transmission system.

The problems met in superimposing high-frequency currents on conductors carrying power at high potential may be divided under the two general headings of *Coupling* and *Transmission*. The problem of coupling high-frequency equipment to high-tension transmission lines was quite novel, and at the outset there was no experience available for guidance. Economic considerations naturally formed a large part of the problem, and are responsible solely for the development and design of several types of coupling capacitors, each type being best suited to a particular field of application.

The transmission of high frequencies over a power network involves very different problems from the transmission of low frequencies over the same network, or from the transmission of high frequencies over telephone conductors. It has been necessary, therefore, to develop a radically different technique for handling power-line communication problems.

The ideal line for the transmission of high frequencies would consist of a single high-voltage transmission line which has no directly-connected branch lines and which may be terminated at its ends in an impedance equivalent to its surge impedance. Such an ideal condition is very seldom realized or even very closely approached in actual practise. Branch lines produce two effects on a carrier communication channel; first, due to the fact that the branch line must be energized as well as the main transmission line a loss of some carrier energy is incurred; and second, a branch line gives rise to reflection. When the carrier-frequency voltage reaches the remote end of the branch line, it is reflected back toward the point of origin and arrives at that point with a phase relation (with respect to the original voltage) which will

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[1] Both of the General Electric Co., San Francisco, Calif.

Presented at the Pacific Coast Convention of the A. I. E. E., Spokane, Wash., Aug. 28-31, 1928.

depend upon the length of the branch line and the frequency of transmission. This reflected wave may therefore either aid or oppose the original voltage. Fortunately, however, in most practical applications the two above effects are either too small to seriously affect communication, or may be avoided to a large extent by a proper selection of operating frequency. Where necessary, the effect of branch lines may be eliminated from the carrier circuit by means of high-frequency trap circuits.

Frequently, it becomes necessary to communicate over a transmission line which is broken permanently by a voltage transformation or frequency changer, or which may be opened by switches. In these cases, it is necessary to provide a means for transferring the carrier energy around the break in the power circuit. The same problem is involved in transferring a communication channel from one transmission system to another.

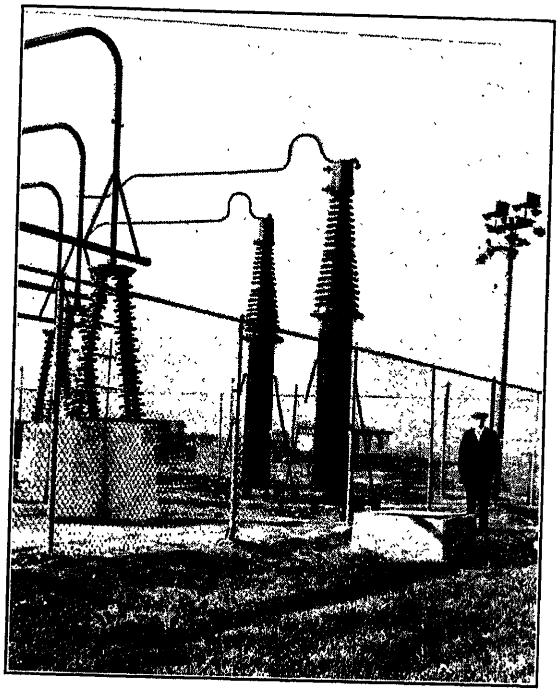
FIG. 2—COUPLING CAPACITORS FOR POWER-LINE CARRIER TELEPHONE

In some cases, the communication distances involved are such that a power in excess of that supplied by the normal transmitter is required. This problem can usually be solved in either of two ways: by increasing the power of the transmitter until sufficient energy is received at the remote point, or by using carrier-current repeater equipment near the electrical center of the transmission system to raise the energy level of the received signals to their original value, and re-transmit them along the transmission system. The latter method has three distinct advantages; first, the total power required to transmit a signal over a long distance is less if a repeater is used than if the signal is transmitted directly; second, the repeater requires no abnormally large output from any of the transmitters and therefore does not increase interference between carrier channels nor greatly increase the probability of interference with broadcast receivers; third, the two remote communicating stations may be using entirely different carrier channels, the transfer in channels being made at the repeater.

It is evident from a consideration of these problems that an equipment designed to provide absolutely satisfactory service for transmission over telephone conductors might be entirely inadequate to provide communication over a power network.

The following description of the available carrier-current telephone equipments developed by the company with which the authors are connected will serve as an indication of the methods used in meeting the communication requirements and in solving the problems related thereto.

Among all types of apparatus complete intercommunication is provided, a single frequency band being employed for each two-way channel.

PRIMARY STATION EQUIPMENT

This equipment has been developed to meet the requirements on trunk channels. The necessary facilities for efficient and economical operation of trunk channels are provided in the following operating features:

1. Full automatic operation is provided from any operator's phone, the necessary procedure in placing or receiving a call being practically identical with that of a conventional wire-line automatic telephone system.
2. A maximum of ten two-wire telephone extension lines may be connected to each station equipment, each line having complete control of the carrier station and being selectively called from any carrier station on the same system. Provision may also be made to allow communication from other telephones connected with private branch exchanges, either manual or automatic.
3. Each incoming telephone line has exclusive and private use of the carrier equipment, and the conversation cannot be interrupted by a party on any other incoming line. An exception to this is that dispatchers' lines, or other designated lines, may be connected for preferred service, thus permitting the operators at designated telephones to interrupt a conversation on any other line and request the use of the carrier channel.

Parties on lines not connected for preferred service receive a "busy tone" if they attempt to place a call when the station equipment is in use.

4. Four-wire circuits may be employed if the noise level on a telephone line is so high as to make it unsuitable for a two-wire extension. When a four-wire circuit is used, the signal input to the line from the operator's telephone instrument may be raised to any desired level by means of simple amplifier equipment, and thus the ratio between signal and noise may be increased. The strength of the audio-frequency input to the carrier

set may be reduced by means of adjustments at the carrier set, so that when an amplifier is used at the operator's end of the line, satisfactory operation may be obtained, even though the noise level on the line is quite high. The service provided over a four-wire circuit is the same as for a two-wire circuit.

5. Provision is made for the application of "inter-system" attachments, to provide communication from the same station equipment over either of two separate carrier channels. Wire-line extensions from a station so equipped may receive or transmit calls selectively over either channel, the selection of channels being entirely automatic. While an operator is engaged in a conversation over one channel, he can receive calls over the other channel.

6. By means of a suitable attachment, high-tension telephone lines can be used for extension service, the operation secured on such extensions being the same as that for "quiet line" extensions.

7. Two primary equipments may be used together for repeating signals on very long channels, or for transferring signals from one transmission network to another. This service will be discussed under a later heading.

SECONDARY STATION EQUIPMENT

Some communicating points do not require all the operating features provided in a primary equipment. A secondary station equipment has been developed to meet this condition economically. Four wires are required for connecting each telephone instrument to the set. When several telephone instruments are used, code ringing is employed. Full selective ringing may be provided by the use of one additional conductor between the set and each instrument.

The apparatus is designed to operate normally from 110-volt a-c. power supply, but may be made independent of the a-c. supply by the addition of a motor alternator operating from a storage battery. Where no a-c. supply is available, this storage battery may be charged from a gasoline-engine-driven generator.

BOOTH EQUIPMENT

This equipment is suitable for communication from isolated points where the communication distances are moderate. It is designed for operation either from dry cells or from a 110-volt a-c. supply. The equipment is mounted in a weatherproof case and when battery operation is used, may be installed on a tower or other convenient location exposed to the weather. This application is intended primarily for use by line patrolmen or service crews, and intermittent service only is provided. When this equipment is used with a-c. supply, full time operation is provided and it is suitable for installation in switching stations and line patrolmen's houses. The equipment includes a small 60-cell storage battery which provides emergency operation during failure of the a-c. supply. The communication provided by this equipment is simplex; that is, the operator employs a push-button on the hand set to change from "receiving" to "transmitting" position.

PORTABLE EQUIPMENT

This equipment is designed to provide communication between any station equipment and fixed points along the transmission line within a radius of approximately 30 mi. It is a self-contained and extremely compact transmitter receiver unit, weighing approximately 15½ lb., and provided with shoulder straps to facilitate carrying. The communication provided is simplex.

INTERSYSTEM EQUIPMENT

This equipment is designed to operate as an attachment to the primary station equipment, permitting the operation of such an equipment on either of two communication channels. A load dispatcher may thus communicate selectively over either his own communication system or that of an interconnecting system. As an alternative, the load dispatchers of two interconnected systems may be provided with a channel separate from those used for system communication.

BY-PASSING EQUIPMENT

When it is necessary to transfer the carrier energy around a transformation, open disconnecting switch, or other discontinuity in the carrier circuit, a by-pass equipment consisting of a series of resonant circuits is employed. Since no vacuum tubes or moving parts are employed the equipment requires only periodic inspection and is therefore suitable for tower mounting at isolated or unattended points.

CARRIER CURRENT REPEATER EQUIPMENT

In discussing the primary equipment, mention was made of the fact that two carrier sets may be used together to comprise a repeater assembly. Such an equipment may be installed to serve two distinct purposes: First, it may be used to raise the energy level on a carrier channel and therefore permit much greater communication distances; and second, it may be used to connect two otherwise independent communication channels and permit either completely independent operation of the two channels or complete intercommunication between stations on the two channels, as desired.

When operating as a normal repeater, the equipment functions as follows: The incoming modulated carrier is received and demodulated in the normal manner. The signal component is then amplified and impressed upon the transmitter operating over the outgoing channel. The apparatus is so designed that a signal which has been received and re-transmitted by the repeater cannot pass back through the repeater to the side from which it was originally received. This is accomplished by apparatus so designed that when one of the transmitters begins to function, the output circuit of its associated receiver is blocked. All tendency toward "feed-backs," which would result in oscillation or "singing" of the repeater circuit, is thereby eliminated. The operations for repeating the signals are identical for both directions.

The repeater equipment is in the operative condition only while actually in use. It is started automatically from a calling station as follows:

An operator desiring to communicate through the repeater station first dials the "repeater exchange" number. This number serves to start the motor-generator set and place the repeater in operation. Any further numbers dialed by the calling operator are repeated over the outgoing channel. The ensuing conversation is similarly transferred from one channel to the other.

When the repeater is placed in operation by an incoming call, a time delay circuit is energized to maintain the apparatus in an operative condition for a definite time interval after the last signal is repeated. At the end of this time interval the repeater apparatus is automatically shut down, thus effecting a saving in operating cost and increasing the operating life of the apparatus to that of a normal station equipment. The time delay feature is provided to prevent the repeater shutting down during pauses in a conversation. The length of time delay is adjustable within wide limits to suit local requirements.

The operator at the repeater station may be provided with automatic selective control, permitting communication over any channel selectively, or over two channels simultaneously. He may monitor the conversations on either side of the repeater or passing through the repeater, or may enter into these conversations.

The operation of a repeater in connection with an intersystem attachment is the same as that of a normal repeater except that the "repeater exchange" number, in addition to placing the apparatus in service, selects the proper outgoing channel.

HIGH-TENSION TELEPHONE LINE EXTENSION

As an extension to a primary station equipment, it is sometimes desired to use a high-tension telephone line; that is, a telephone line so situated in the proximity of a high-voltage transmission line that the extraneous voltages induced in the telephone line are relatively great. Such a line is unsuited for direct connection to a primary carrier set. In order to eliminate the effects of power frequency induction, a special form of extension equipment may be employed on any high-tension telephone line over which successful voice-frequency communication may be provided. This type of extension employs carrier-frequency transmission from the remote operator to the primary carrier set, and voice-frequency transmission from the set to the operator.

The use of a high-frequency carrier for transmission from the remote operator to the station apparatus makes it possible to eliminate power-frequency voltages from the input to the station transmitter, by means of filters which do not pass the low frequencies. The use of these filters also makes it possible to separate the incoming from the outgoing signal without the use of balancing networks such as are used with voice-frequency telephone repeaters. The amplification afforded by this type of extension apparatus is such that the length of telephone line that can be used is much greater than in the case of the usual two-wire extensions as designed for quiet lines.

The telephone line used in connection with a high-tension extension does not necessarily constitute a complete d-c. circuit, and can be used, therefore, with the normal insulating and drainage transformers and protective devices. The protection afforded the operator from voltages induced on the telephone line by power circuits or lightning is even better than that provided when employing such a telephone line in the normal manner.

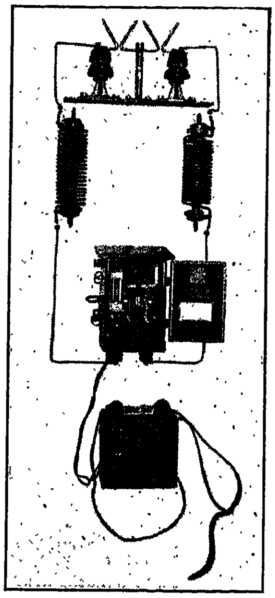

FIG. 3—PORTABLE CARRIER-CURRENT TELEPHONE

With connection box and protective equipment for coupling unit installation.

MULTIPLEX CARRIER CHANNELS

Because of their peculiar advantages, the demand for additional uses of carrier current channels is growing. These are for relaying sections for line, distant control of switches, telemetering, and frequency transmission. Fortunately, a pair of coupling capacitors may be used for the simultaneous transmission of more than one carrier frequency. Lines using capacitors for carrier telephony at the outstart are now being equipped with these later developments.

The number of additional channels it is possible to operate without interference is limited, and it is obviously most desirable to employ but one frequency per channel. The development of the single-frequency duplex-carrier telephone some years ago has been most helpful in this regard.

NEW USES FOR CARRIER CURRENT

In general, a carrier-current channel can be made to accomplish what would otherwise require a separate pair of wires, without the investment and maintenance charges of the latter. When the distances involved are sufficient these factors result in distinct monetary and operating advantages in favor of the carrier channel.

New applications are arising daily. An interesting example is the case of a large pumping load supplied by one power system, but scattered over a large territory. These motors may be controlled at will by carrier current over the distribution system, thereby making it possible to reduce the peak and improve the load factor.

In another instance, it is desired to transmit the frequency of one generating station to another, and carrier current offers a ready solution. There are, no doubt, numerous other operating situations wherein carrier-current methods present the best engineering solution.

Problems in Power-Line Carrier Telephony
And Recent Developments to Meet Them

BY W. V. WOLFE* and J. D. SARROS*
Member, A. I. E. E. Non-member

INTRODUCTION

POWER-LINE carrier telephone systems have been in operation in this country for the past six years. This form of communication may be used either as a primary means of telephone service for the transaction of dispatching and other business, or it may be employed chiefly as an emergency service to supplement facilities the power company already has at its disposal.

To date, several types of equipment have been designed to meet these needs. However, the growing complexity of power systems, involving a higher standard and more comprehensive communication service, indicates the desirability for a better type of carrier circuits and equipment. The purpose of this paper is to outline in general the difficulties to be met in applying high-frequency communication to power systems, and to describe a recent development in equipment for this class of service.

THE PROBLEM

The problem of providing high-frequency communication over power circuits must first be considered from the angle of the general purpose of this type of communication. Formerly, power-line carrier telephone circuits were considered primarily as channels for load dispatching business. While the primary use is for load dispatching work, there is also considerable demand for such circuits to be used for general business transactions. For load dispatching service only, the circuit may be an isolated one, providing communication from the dispatcher to one or more generating or sub-stations, but this may not meet load dispatching requirements and is rarely satisfactory for general business. It therefore becomes desirable to make the carrier circuit a coordinated part of the entire communication system of the power company.

Considering the general circuit requirements we find that these in general have not changed. Stable, reliable circuits of good quality and with low noise have been required from the start. One factor which perhaps has increased in importance is the requirement that the equipment itself be designed for sufficient flexibility to permit of adapting it to all the different conditions encountered on power circuits. Another factor which, while not previously overlooked, has risen to considerable prominence recently, is the necessity for multiple channel operation on any given power circuit without interference between channels.

CHARACTER OF THE TRANSMISSION MEDIUM PRESENTED BY A POWER NETWORK

In designing apparatus to provide communication service, the most important consideration is the character of the transmission medium to be employed for the communication channel.

Earlier investigations[1] showed the superiority of a full metallic circuit over a ground return circuit both from a standpoint of attenuation and stability as well as noise. Over the range from 50 to 150 kilocycles the attenuation of the power line without branch lines or connected apparatus has been found to be of the order of 0.05 to 0.1 $T\ U^2$ per mi. This loss is very low and indicates the possibility of securing excellent communication under such conditions. Unfortunately, power circuits are not ordinarily simple straightforward circuits but involve branch lines, closed loops, and other irregularities which radically change their character as a transmission medium.

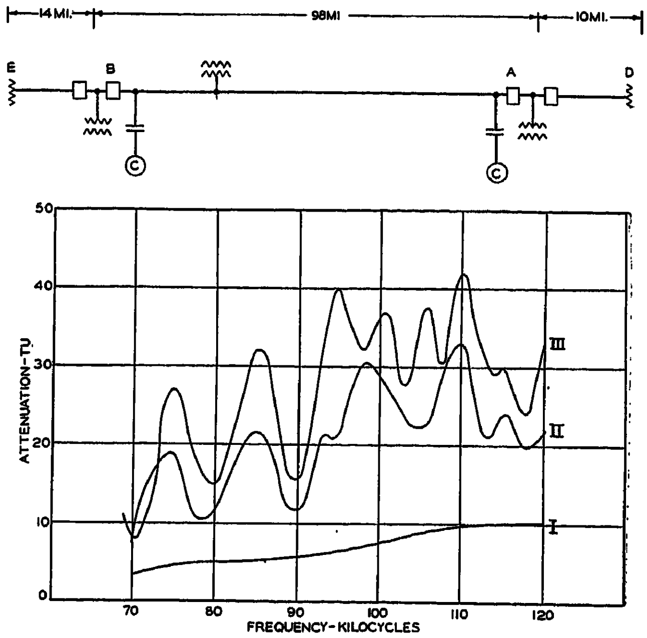

FIG. 1—EFFECT OF LINE SWITCHING ON THE ATTENUATION CHARACTERISTIC.

As a concrete example of these facts there is shown on Fig. 1 a power network involving a 110-kv. line with carrier terminals located at A and B, a distance of about 98 mi. Fig. 1 also shows the attenuation frequency characteristics made on this line under three different conditions. Curve I gives the characteristic of the line $A\ B$ which was, for this test, entirely isolated

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*Both with Bell Telephone Laboratories, New York, N. Y.

Presented at the Pacific Coast Convention of the A. I. E. E., Spokane, Wash., Aug. 28-31, 1928.

1. For references see Bibliography.

from the system except for a transformer bank 23 mi. from B. Curve II shows the characteristic of the same line with the 14 mi. circuit $B\ E$ and its associated equipment connected. It is evident that the introduction of this circuit not only increases the average attenuation of the line $A\ B$ but also introduces serious irregularities caused by reflection and absorption effects. Thus, in a 5000 cycle interval, there is, under this condition, as much as 10 $T\ U$ variation in attenuation. Curve III shows the characteristic of this same section $A\ B$ with both $B\ E$ and a 10 mi. branch $A\ D$ with its associated equipment connected in at the other end. Again we have an increase in average attenuation. The irregularities due to reflections are now so pronounced as to give a 20 $T\ U$ variation in attenuation over a 5000 cycle interval. There may be no similarity between the last two conditions; that is, the peaks and troughs in attenuation may not occur at the same frequencies. Thus, we not only have *irregularities* in the high-frequency characteristics but *instability* as well.

Due to the dependence of carrier-frequency characteristics upon line and switching conditions, it is often difficult to find a suitable carrier-frequency band which will insure satisfactory operation of power-line carrier equipment for several line or switching conditions. This difficulty increases with the size and complexity of a power distribution system. If two frequency bands are required to provide communication, the problem is even more complicated.

A slight change in the line conditions may appreciably alter the carrier-frequency transmission characteristic and may therefore seriously affect the operation of a carrier system. A carrier-frequency band which may have been selected as the result of considerable effort and which may be very satisfactory for a given condition is often rendered absolutely useless by a change in the line conditions.

A knowledge of the noise conditions likely to be encountered on power networks is likewise necessary for the correct design of the carrier terminal equipment but unfortunately the factors involved here are many and of varied character. Among these sources of high-frequency noise may be mentioned corona and leaky insulators. The latter trouble may be due to faults in the insulators or to collection of dust or other foreign material on the insulators. A prolific source of noise has been found in the spitting or arcing which occurs between the power conductor and metal objects close to the conductor but not connected to it. For example, on a particular power system the carrier installation was started and completed during a relatively wet season and after the installation the circuit became excessively noisy. The source of this noise was traced to 12 lightning-arrester choke coils of the strain type. In each of these choke coils there was a number of iron bolts employed in the reenforcing of the coil but not in contact with the conductor. During the dry season there was a continuous spark from the closest point of the power conductor to each one of these bolts. Bonding these bolts to the conductor removed this noise entirely.

The presence of corona on a power circuit introduces a very interesting possibility from the standpoint of noise production. Considerable light is thrown on this subject by the researches on corona by Dr. Harris J. Ryan[3] and his associates. Dr. Ryan has disclosed the existence of a space charge surrounding a conductor in corona. This space charge results in an effective change, at periodic intervals, in the electrical diameter of the conductors. Effective conductor variations occurring as indicated by Dr. Ryan would cause the attenuation of the power circuit to vary and thereby produce modulation on the line itself. The modulation between the carrier frequencies as a function of this varying attenuation will result in noise after the carrier signal has been demodulated. If such is the case, the amount of noise observed in the voice frequency range would increase directly as the transmitter power in the carrier circuit was increased and it might therefore develop that the operation of a carrier system on such a power circuit could not be insured by the simple expedient of increasing the transmitting power.

It is evident from these observations that the successful operation of carrier communication over power lines does not depend alone on the development of the carrier apparatus. The transmission line is a very important link in the system and can vitiate the performance of otherwise perfect equipment.

FUNDAMENTAL CIRCUIT CONSIDERATIONS

Bearing in mind the service requirements and the character of the transmission medium, as briefly described, we may now consider the fundamental types of circuits available for high-frequency communication on power lines.

It is scarcely necessary to mention simplex or manual switching from the transmitting to the receiving condition as a method of operating these circuits since such a scheme is very cumbersome and does not permit coordination with other telephone circuits. Full duplex operation can be obtained by using two independent pairs of wires or circuits, one circuit for transmission in each direction. This method is highly satisfactory but in this case is uneconomical since it requires two independent circuits for a given conversation. To obtain duplex or automatic two-way operation when one circuit is used for both transmission and reception, means must be provided for separating the transmitted and received currents. This is generally done by using any one or a combination of three general methods:

1. Frequency separation.
2. Balance or bridge method of separation.
3. Use of voice controlled relay circuits.

Frequency separation involves the use of two frequencies, one for transmitting in each direction. Selection between the two is obtained by the use of selective circuits or filters of high transmission loss to the unwanted frequencies and low loss to the desired frequencies.

Separation by the use of balance or bridge methods is extensively used in the communication art where the lines are electrically long and their impedances remain substantially constant. In general, the transmitting circuit may be connected across one diagonal of an a-c. bridge and the receiving circuit across the other. The transmission line is connected to one arm and the bridge standards or network to the other arm of the bridge. So long as the bridge standard, or network, matches the impedance of the line at each frequency used, no energy will be transferred from transmitter to receiver.

An automatic two-way circuit which in its operation is essentially a duplex circuit may be secured by the use of voice controlled relay circuits. These circuits may employ mechanical relays or vacuum tube circuits for their operation. In either event the transmitting circuit is rendered inoperative during the receiving interval and conversely the receiving circuit is inoperative during the transmitting interval.

Where the voice controlled relay circuits are used the same band of frequencies is normally employed both for transmitting and receiving although this is not a fundamental requirement of the system. The balance or bridge method of separation may also be employed on a single frequency circuit.

Perhaps the most important consideration is the type of high-frequency transmission to be employed. There are three commonly used systems:

1. Systems transmitting the carrier and both side-bands.
2. Systems transmitting the carrier and one side-band.
3. Systems transmitting one side-band only.

When two frequencies, such as a speech frequency and a carrier frequency, are properly introduced into the ordinary vacuum tube modulator, the products of modulation consist of the sum and difference of these two frequencies, called respectively the upper and lower side-band, and the carrier frequency, besides other modulation products which may be neglected in this discussion. The demodulator performs the same functions as the modulator but in reverse order; that is, it receives the two side-bands and the carrier and resolves them so that one of the products of demodulation is the original speech. The two side-bands are each of the same frequency width as the original speech. Furthermore, these side-bands are symmetrical in position with respect to the carrier frequency and each side-band by itself contains all the elements necessary to transmit the original speech.

Obviously, therefore, it is not necessary to transmit both side-bands with the carrier since the original voice frequencies may be faithfully reproduced by demodulation between the carrier and either the upper or the lower side-band. Furthermore, the carrier is a constant frequency whose amplitude need not vary with the amplitude of the voice. The carrier may be suppressed at the transmitting terminal after modulation has taken place, and be re-introduced at the receiving terminal for demodulation.

The system transmitting the carrier and both side-bands is that employed for broadcasting and prior to this time for all power-line carrier telephone circuits. This type of system requires a frequency band of approximately 5000 cycles in width for the transmission of speech having reasonably good quality.

A system transmitting the carrier and one side-band has essentially the same features as that transmitting the carrier and both side-bands except that the band width may be reduced to approximately 2500 cycles for the same quality.

The third system in which the side-band alone is transmitted requires supplying the carrier locally to the receiving circuit. This system also employs a frequency band of 2500 cycles for comparable quality.

Two general methods of coupling to the power line are available. These are antenna coupling and condenser coupling. The present tendency seems to be so largely toward the use of condenser coupling that it is scarcely necessary to discuss their respective merits.

CHARACTERISTICS OF THE NEW POWER-LINE CARRIER TELEPHONE SYSTEM

From consideration of the service requirements, the line characteristics, and the circuits available, a single frequency, single side-band, carrier suppressed system has been adopted as the most efficient and reliable means of getting satisfactory communication over power circuits.

With the foregoing as a basis we may now consider some of the improvements effected by this new power-line carrier telephone system as compared first with a two-frequency system, and second with a single-frequency carrier transmitted system.

Its advantages over a two-frequency system are as follows:

1. Less likely to be affected by the irregularities and instability of power-line high-frequency characteristics.
2. Transmission loss in each direction is the same.
3. Party line conversation practicable.

Carrier suppression and the use of a single side-band gives it the following additional advantages.

4. More easily adaptable to single-frequency operation.
5. Gives better quality through irregular line characteristics.
6. Ordinary line noise and noise due to any line modulation is more effectively subordinated.
7. Frequency conservation makes multi-channel operation easier.
8. Received speech level is less affected by line attenuation changes.
9. It has a greater transmitting range for the same power.

10. Lower transmission loss and greater selectivity secured in coupling to power line.

The question of the irregularity and instability of the line attenuation characteristic and its effect on the operation of any system has already been referred to. Although the use of the same band of frequencies for transmission and reception simplifies the problem, this advantage is enhanced by the use of a single side-band system since the required frequency band is a minimum. This is a distinct advantage because cases have been met where the peaks in the frequency spectrum were extremely sharp and only one frequency band offered good operation under all line conditions.

It is obvious that the transmission in each direction with any single-frequency system is the same.

Party line conversations are not practicable with a two-frequency system, although it permits "broadcasting" instructions to all terminals on the line. With a single-frequency system, instructions may be issued to all operators simultaneously, and a general discussion can be carried on between terminals.

Single side-band transmission simplifies the problem of obtaining automatic two-way operation by the use of voice operated vacuum-tube relay circuits since there is no output from the transmitter so long as there is no input into the microphone.

Single side-band transmission gives better quality through irregular line characteristics by virtue of the fact that the band width is narrow.

It is apparent that a system with such a high degree of selectivity will be less sensitive to interference either from line noises or from other carrier channels. Conversely, since a very narrow band is transmitted, the possibility of its interfering with other systems or channels is reduced to a minimum. There is the added advantage that interference from noise as a result of possible line modulation is reduced.

Since in single side-band transmission the frequency band is only half as wide as is required with double side-band transmission, the conservation of frequency spectrum resulting thereby facilitates multi-channel operation. Because of the use of balanced double demodulation and the fact that the transmitted band is reduced to a minimum, a very high order of selectivity is obtained.

It can be shown that the amplitude of the received signal is a function of the amplitudes of the carrier frequency and of the side-band frequency. For this reason, variations in the transmission loss may cause a greater change in the amplitude of the received speech of a carrier transmitted system than of a carrier suppressed system. For a carrier transmitted system, the amplitude of the received speech may vary at a greater rate than the changes in the transmission loss, since the amplitudes of both carrier and the side-band are correspondingly varied. For a carrier suppressed system, the amplitude of the received speech changes in the same ratio as the transmission loss, since only the amplitude of the side-band is affected and the amplitude of the locally supplied carrier remains constant.

Assuming the maximum of 100 per cent modulation for a system in which the carrier and both side-bands are transmitted, 50 per cent of the transmitted energy is associated with the carrier. For ordinary modulation we can say that 100 watts of single side-band energy is approximately equivalent to 500 watts where the carrier and both side-bands are transmitted. Thus, by suppressing the carrier and transmitting one side-band only, we increase the efficiency of the system by at least 400 per cent.

The fact that a narrow band is transmitted makes possible the use of relatively low capacity coupling condensers and consequently, a coupling filter of high efficiency and maximum selectivity can be designed. Additional selectivity through filters is provided at the input of the first demodulator, between the first and second demodulator, and at the output of the latter.

Description of Circuits

At the risk of repeating much that has already been written[4] we shall now discuss in general the fundamental principles underlying the operation of this new power-line carrier telephone equipment. The satisfactory performance of a single side-band carrier suppressed system depends to a great extent on the solution of the following problems:

1. The sufficient suppression of the carrier at the transmitting end.
2. The elimination of the undesired side-band.
3. The design of high stability oscillators.

From the standpoint of fundamentals, it is obvious that the incomplete suppression of the carrier and undesired side-band and their reception by the distant demodulator, will not cause distortion if the "carrier leak" of the transmitting station and the carrier supplied at the receiver are in synchronism. The oscillators used to supply high frequency for modulation and demodulation are of extremely high stability and have proved very satisfactory. However, synchronism cannot be realized in practise and measures are taken for suppressing to the desired degree the carrier and unwanted side-band in order to circumvent the slight discrepancy between the modulating and demodulating carriers. Balanced or push-pull modulators, as employed here, suppress the carrier to a considerable extent. Further attenuation is obtained by locating the frequency of the carrier at a point beyond the cut-off of the attenuation characteristic of the band pass filter used for eliminating the undesired side-band. Any carrier that may be transmitted under these conditions is further prevented from causing trouble by the use of balanced demodulators.

Another interesting phase in connection with this problem is the use of double modulation and demodulation. Although this scheme of modulating twice provides added selectivity, the reasons that lead directly to its adoption are as follows. At power-line carrier telephone frequencies, that is, the band from 50 to 150 kc., the manufacture of suitable band pass filters to suppress the unwanted side-band is very difficult and correspondingly expensive. Assume, for instance, that a 2000-cycle tone modulates a 100-kc. carrier frequency. The resulting side-band frequencies are 98 kc. and 102 kc. It is difficult to build a selective circuit to select one of these frequencies to the complete exclusion of the other. The problem becomes still more difficult at the lower voice frequencies as, for instance, 400 cycles. In this case, the resulting side-band frequencies are 100.4 kc. and 99.6 kc. However, if double modulation is employed, the side-bands can be given a wide frequency separation, thereby greatly facilitating the selection of one side-band to the complete exclusion of the other and of the carrier frequency. Assume that a 2000-cycle tone modulates a 30-kc. carrier frequency. The resulting side-band frequencies will be 32.0 kc. and 28.0 kc. These can be separated by a commercial band pass filter. Further assume, that the lower side-band, 28.0 kc., is selected and modulates a 100-kc. carrier frequency. The resulting side-bands will be 128.0 kc. and 72.0 kc. Either one of these side-bands can be separated from the other by comparatively simple selective circuits. It is also obvious that the side-band frequency that is put on the line can be varied to suit a particular line by merely varying the second carrier frequency and leaving the first carrier frequency fixed. Thus, double modulation provides a convenient and simple means for obtaining the advantages of a single side-band suppressed carrier system at power-line carrier telephone frequencies.

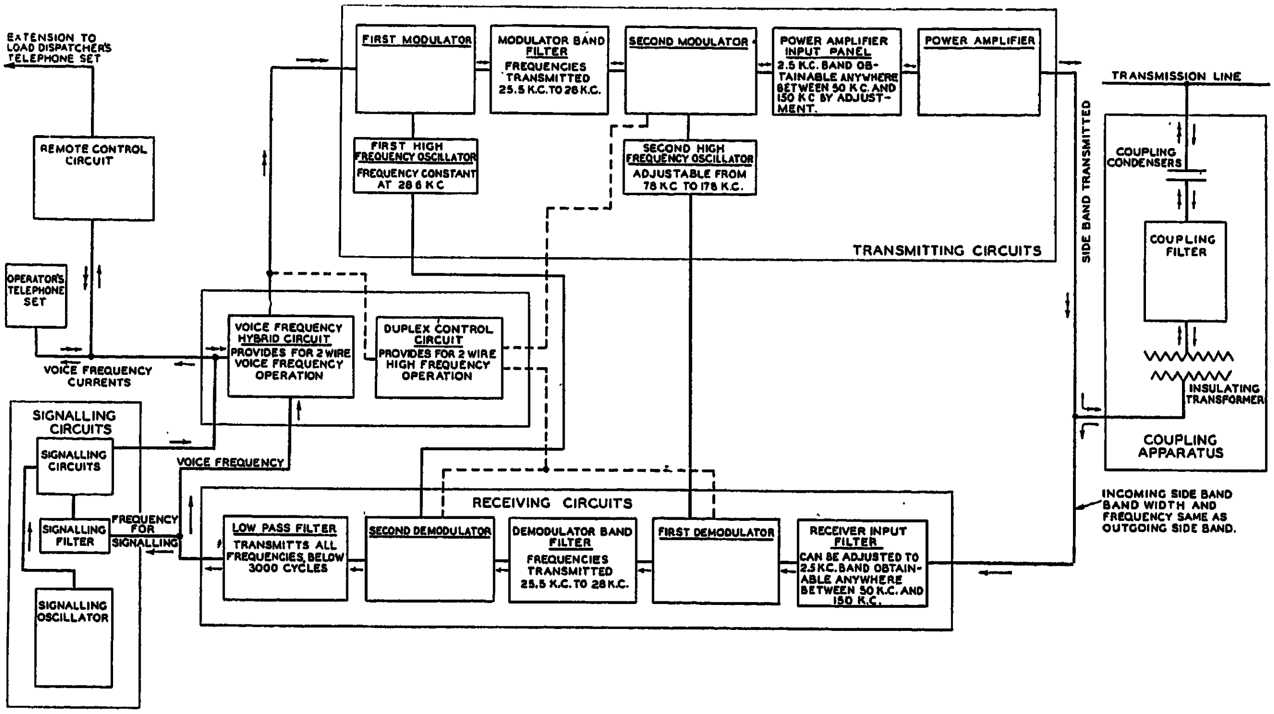
EXTENSION TO LOAD DISPATCHER'S TELEPHONE SET
REMOTE CONTROL CIRCUIT
OPERATOR'S TELEPHONE SET
VOICE FREQUENCY CURRENTS
FIRST MODULATOR
MODULATOR BAND FILTER
FREQUENCIES TRANSMITTED 25.5 K.C. TO 28 K.C.
SECOND MODULATOR
POWER AMPLIFIER INPUT PANEL
2.5 K.C. BAND OBTAINABLE ANYWHERE BETWEEN 50 K.C. AND 150 K.C. BY ADJUSTMENT.
POWER AMPLIFIER
FIRST HIGH FREQUENCY OSCILLATOR
FREQUENCY CONSTANT AT 28.6 K.C.
SECOND HIGH FREQUENCY OSCILLATOR
ADJUSTABLE FROM 78 K.C. TO 178 K.C.
TRANSMITTING CIRCUITS
SIDE BAND TRANSMITTED
TRANSMISSION LINE
COUPLING CONDENSERS
COUPLING FILTER
INSULATING TRANSFORMER
COUPLING APPARATUS
VOICE FREQUENCY HYBRID CIRCUIT
PROVIDES FOR 2 WIRE VOICE FREQUENCY OPERATION
DUPLEX CONTROL CIRCUIT
PROVIDES FOR 2 WIRE HIGH FREQUENCY OPERATION
SIGNALLING CIRCUITS
SIGNALLING CIRCUITS
SIGNALLING FILTER
FREQUENCY FOR SIGNALLING
SIGNALLING OSCILLATOR
VOICE FREQUENCY
RECEIVING CIRCUITS
LOW PASS FILTER
TRANSMITTS ALL FREQUENCIES BELOW 3000 CYCLES
SECOND DEMODULATOR
DEMODULATOR BAND FILTER
FREQUENCIES TRANSMITTED 25.5 K.C. TO 28 K.C.
FIRST DEMODULATOR
RECEIVER INPUT FILTER
CAN BE ADJUSTED TO 2.5 K.C. BAND OBTAINABLE ANYWHERE BETWEEN 50 K.C. AND 150 K.C.
INCOMING SIDE BAND BAND WIDTH AND FREQUENCY SAME AS OUTGOING SIDE BAND.

FIG. 2—BLOCK SCHEMATIC OF SINGLE-FREQUENCY DUPLEX POWER-LINE CARRIER TELEPHONE SYSTEM EMPLOYING SINGLE SIDE-BAND SUPPRESSED CARRIER TRANSMISSION

It is not necessary to employ double demodulation, when double modulation is used. The original message may be obtained from the side-band by supplying the proper carrier frequency, which is equal to either the sum of or the difference between the two modulating frequencies, depending upon whether the upper or lower side-band is transmitted. For instance, in the case above, if the 72 kc. side-band is demodulated by a 70 kc. carrier frequency, the resulting side-band will be 2000 cycles, which is the original tone. Such an arrangement, however, requires at least 3 carrier-frequency generators at each terminal, two to supply the modulating frequencies and one to supply the demodulating frequency. If double demodulation is employed in a system using the same band of frequencies for transmission and reception, the same carrier frequencies may be used for both modulation and demodulation but in the reverse order.

In the case of the system under consideration, duplex or automatic two-way operation is obtained by the use of voice operated vacuum tube "relay circuits." This is effected by rendering either the transmitter or receiver inoperative by causing the voice itself to control a heavy negative grid bias on the modulator and demodulator tubes. There is also provided an interlocking device which prevents incoming energy or room noise from rendering the transmitting circuit operative while receiving. Essentially this same scheme is employed in the transatlantic radio circuit.[5] It has also been in use for years in long cable toll circuits where echo suppressors[6] have been found to be indispensable.

The block schematic of the system, shown in Fig. 2, indicates how voice or signaling currents are modulated twice, before being amplified and passed to the transmission line; also how the incoming high-frequency currents are demodulated twice before being passed to the voice-frequency line. This diagram indicates the use of the same oscillators for the modulators and demodulators. The duplex control circuit which provides for single-frequency operation, and the voice-frequency hybrid circuit which makes possible the extension of the communication service on a two wire basis to a distant point, are other features of this system. Two-wire remote control may be provided on these circuits.

In view of the fact that past experience indicates that the power supply has furnished one of the main sources of maintenance troubles, special attention was given to the design of the power supply equipment for this system. All power for plate and grid potentials is derived from vacuum-tube rectifiers. The filaments for the low-power tubes may be supplied from a 30-volt storage battery. The operation of the terminal is dependent upon the continuity of the a-c. power supply and therefore an emergency power supply source may be desirable. Such a source can readily be secured from a motor-generator set driven from the station storage battery and delivering a suitable a-c. voltage.

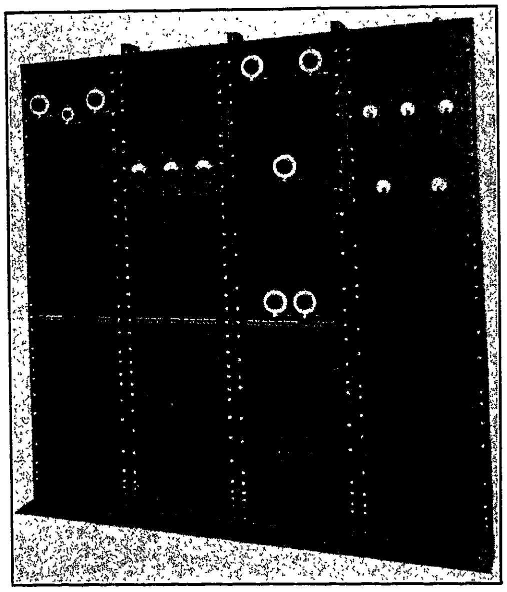

Fig. 3—Front View of Equipment

Fig. 3 shows a front view of the equipment. Switchboard type of mounting has been followed in that all apparatus with the exception of meters and controls is mounted on the back of the panels. The rear view, Fig. 4, shows the locker type of back cover that has been adopted for this equipment. Fig. 5 shows the 220-kv. condensers used to couple this equipment to the line. The box between the two bus towers near the foreground, houses the coupling filter. This filter may be adjusted to pass efficiently a frequency band of 2500 cycles anywhere in the region of 50 to 150 kc.

Initial Installation

Three terminals of this new equipment are now in operation on the lines of the Pacific Gas & Electric Company. They have provided a communication service over power circuits which have presented very serious communication difficulties to other apparatus previously tried. The high-tension circuit over which this equipment operates, consists of the 202-mi., 220-kv. lines from Pit No. 1 Power House to Vaca Dixon Substation and of the 58-mi., 110-kv. lines from this point to the Claremont Substation in Berkeley. From Claremont to the load dispatcher in Oakland there is a five mile two-wire low frequency extension of underground cable with remote control at the dispatcher's office. The voice-frequency circuit may be extended from the dispatcher's office or any of the carrier terminals by connection to other two-wire telephone circuits.

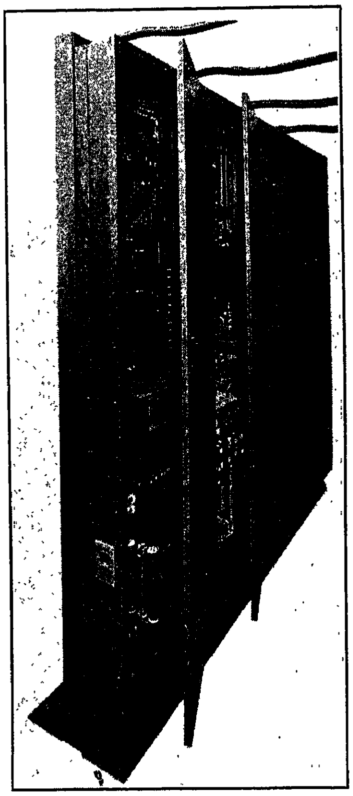

Fig. 4—Rear View Showing Locker Type of Back Covers

There are three points of particular interest in this installation. First, the 58-mi. section is part of one of the largest 110-kv. networks in the country and potentially therefore subject to wide changes in its high-frequency characteristics. Second, the transfer of the high-frequency energy from the 110-kv. line to the 220-kv. line, and vice versa, is accomplished through a by-pass or filter circuit without the use of a repeater. Third, this particular 220-kv. line presents an unusually difficult problem because of the large amount of high-frequency noise present. This noise is probably produced from two major sources—corona and static discharges between the line conductors and the corona shields.

CONCLUSION

The terminal equipment described in the foregoing discussion represents a distinct advance and employs the circuits and apparatus best suited for our present conception of the service requirements and our present knowledge of power-line conditions at carrier frequencies. It must be remembered, however, that power lines as at present constructed and operated present an uncertain medium for communication and that although this equipment overcomes to a large extent these difficulties, the effectiveness of power-line carrier telephony would be considerably enhanced by an improvement in the transmission medium.

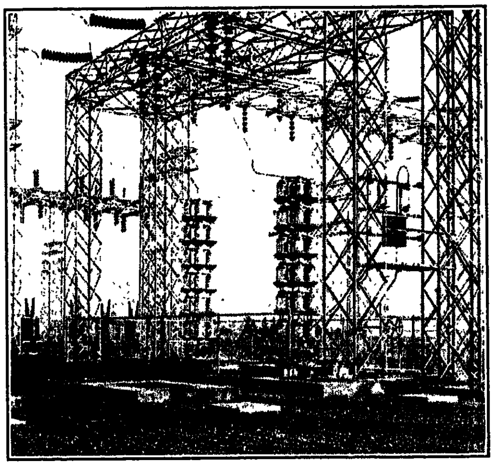

FIG. 5—220-KV. COUPLING CONDENSERS

Some work has been done on methods for stabilizing power-line conditions at high frequencies but so far the results have been meager and the apparatus developed has not met with general approval. Considerable work remains to be done on this problem. Its satisfactory solution will materially increase the effectiveness of power-line carrier telephone circuits. These improvements, of course, will in no way detract from the superiority of the single-frequency, single side-band carrier suppressed system herein described.

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Discussion

L. M. Ilgenfritz: It may be of interest to compare a few of the major problems arising in connection with the development of power-line carrier systems with those of carrier systems for telephone lines such as are described in the paper[1] presented at the recent Denver convention by Affel, Demarest, and Green, and the paper[2] presented at this sesssion by Black, Almquist, and myself.

The earlier developments in carrier systems used in the Bell System passed through several stages in which commercial trials were obtained of both the carrier-transmitted type and the carrier-suppressed type of system. The superiority of the carrier-suppressed systems was so marked that the carrier-transmitted type has become obsolete and is no longer manufactured.

In providing telephone service, it is of course essential to provide for ultimate growth of service and for that reason it is desirable to design such carrier systems so that a maximum number of channels can be ultimately provided on a pole line. The limitations in providing additional service on telephone lines are found in the characteristics of the line circuits themselves. Inter-system interference, controlled by transposition design, of course, limits the number of channels which can be placed on a pair of wires. The difficulty of laying out satisfactory transposition designs increases rapidly with frequency. The frequency space occupied by the channels is consequently at a premium. Therefore, the single-band type of system is the only one which has been considered for use on these telephone lines.

As power networks are interconnected more completely, and the demand for communication facilities by this carrier method increases, undoubtedly the type of system which makes a most economical use of the frequency spectrum and transmits a minimum of non-useful high-frequency current into the power network will be the most desirable for general use.

It may be noted that while this method of duplex or two-way operation, described in the paper, possesses certain advantages in connection with power-line carrier, this method is not so advantageously applicable to carrier systems on telephone lines.

In the latter case, the problem is one of obtaining a maximum carrier use of a telephone pole line as a whole, involving a large number of pairs, each pair carrying a number of channels. It turns out that the most satisfactory arrangement for reducing crosstalk between the various pairs of the pole line and of effecting a maximum total carrier development of the pole line, dictates the use of separate bands of frequencies for transmission in the two directions. For this reason, the present standard types of carrier systems used in the Bell System are lined up on the basis that transmission in the two directions is upon different frequency bands.

J. P. Jollyman: The Pacific Gas and Electric Company was led to install the carrier telephone system described by Messrs. Wolfe and Sarros by reason of the necessity of maintaining communication between the terminals mentioned and by the knowledge that the wire line is subject to interruption especially in the mountain section which follows the highway through a heavily timbered area subject to heavy snow. While the power line passes through the same region its greater mechanical strength and cleared right-of-way renders it practically free of interruption, hence the desire to use the power line for a communication channel.

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[1] *Carrier Systems on Long Distance Telephone Lines,* A. I. E. E. Quarterly TRANS., Vol. 47, October, 1928, p. 1360.

[2] *Carrier Telephone System for Short Toll Circuits,* see p. 117.

The carrier system has been in regular operation for several months and has been very satisfactory. The quality of speech transmitted is excellent. Practically no maintenance has been required. No tuning of the oscillators has been required, although it had been anticipated that some tuning would be necessary. The circuit is in regular use. Wire-line extensions, especially on the power house end, are frequently used to enable the dispatcher to reach the other plants in the region. No difficulty is experienced in using a wire-line extension up to 70 mi. of copper circuit and during emergencies longer circuits have been used.

The performance of the carrier circuit has been observed under a number of special conditions of the power system. It is not interrupted by power-line switching or even by power-line trouble. Switching out one of the 220-kv. circuits results in a slight improvement in the carrier but switching out one of the 110-kv. circuits has little if any effect. The power system has been so arranged as to open the direct 49-mi. path for the carrier between Claremont and Vaca and substitute a path some 250 mi. in length. Under these conditions the carrier circuit continued to give satisfactory communication between these points. A number of other power system changes has been made with little effect on the carrier.

L. J. Neuman: Mr. Wolfe mentioned modulation of the carrier by the corona discharge. May we have a further word of explanation concerning this peculiar phenomenon? Also, I believe the term corona is used quite differently by various engineers and physicists. In order to clarify this discussion would you please define, Mr. Wolfe, what you mean by the term corona?

Roy Wilkins: I have been closely in touch with the carrier-current development on the Pacific Gas & Electric system during the past six years.

I should like to emphasize several points in connection with the paper by Wolfe and Sarros on the final installation by this company.

It must be remembered that the circuit chosen was a particularly difficult one as regards carrier communication. It was chosen in order to be sure that future requirements could be cared for with the same equipment.

As to the sets themselves, single-sideband carrier-suppressed sounds formidable to a power engineer, yet the physical equipment is the simplest mechanically that I have ever seen, including the original simplex.

Mechanically moving parts are reduced to a minimum; even the power supply is a tube rectifier. This has now given three months continuous service without maintenance or interruption.

The voice-operated blocking arrangement as described is carried out by grid-bias on the modulator tubes. It is operating in 0.002 sec. and is adjustable downward.

This is faster action than could be obtained by blocking the oscillator on account of the nature of the circuits.

Another point of interest is that the over-all frequency characteristic is as good as a great many, and better than some, leading makes of present-day broadcast receivers between 400 and 2900 cycles.

One of the troubles encountered was a great deal of noise. As pointed out, the system of double demodulation used gives a signal noise ratio of 15 to 1 as compared to a simple tuned detector.

The line modulation mentioned has been the occasion of much discussion and some study. Its effect on the carrier, however, will be a matter of speculation until specific quantitative measurements either establish or disprove it.

Its effect if present would not appear as 60 cycles, but as a noise covering a wide band.

The remedy for such conditions already applied to telephone toll lines and the now familiar transatlantic telephone channel was some form of single-sideband transmission using a very narrow channel.

Carrier-current communication is essentially a long-haul facility which will probably not supplant entirely the wire line on most power networks, but rather act as a separate means of communication between the more important points.

C. A. Boddie: The general ideas set forth in the first part of this paper are in close agreement with views which I have advanced actively from the time telephone communication over power lines was first undertaken. That a power line is a difficult medium for communication ought to have been apparent at the start. The first difficulty is due to noise arising from spitting insulators and the like, and the second is the ever changing character of the circuit due to switching.

I feel that the whole development of power-line communication has been seriously retarded by the failure to recognize the various factors as pointed out here, and by not making the necessary provision for them in commercial designs. No doubt the basic assumption that a power line is a simple circuit comparable to an ordinary telephone line, led to the development of equipment similar to that used on telephone lines, and having a normal output of communication energy of only 1 watt.

It now seems to be clearly recognized that the standards of communication required by a power company are much more rigid than those applying to an ordinary telephone circuit. The great importance and value of communication to a power company, together with the natural difficulties involved, offer to the engineer a problem of considerable magnitude.

The type of equipment proposed by the authors was developed in order to meet conditions such as encountered on the 220-kv. lines of the Pacific Gas and Electric Company. The authors state that the standard commercial equipment used in attempting communication over this line failed because of the natural difficulties presented by the power line itself, and by the inadequacy of the design. It is unsound, however, to assume that the failure of a particular design necessitates the abandonment of the entire scheme, and the development of new and totally different methods.

As a result of the difficulties encountered in applying their standard equipment to the particular 220-kv. line mentioned in the paper, it was assumed that there was something about a 220-kv. line in general, which made it impossible as a circuit for telephone communication. It was believed that corona was the immediate cause of the difficulty. The theory advanced was that the electrical diameter of the conductor varied with the power frequency, and therefore produced modulation of the communication current.

As a result of actual experience with this particular line and tests which I personally directed, it is my opinion that corona is not responsible for the difficulties encountered in communication over this line. A 220-kv. line is not inherently and fundamentally different from any other line. It is likely to be more noisy because of the higher voltage. The particular line in question was indeed very noisy, in fact much more noisy than there is any need of. This noise was found to be due to discharges between the corona shields and the supporting hardware. At night it was common to see the discharge take place on numerous insulators between the corona shield and hardware. This type of discharge sets up oscillations of sufficient magnitude to interfere seriously with communication currents. This source of noise can be avoided by making a firm electrical connection between the corona shield and the hardware.

In support of my opinion that communication is not made impossible by corona, I can state that thoroughly satisfactory communication of high quality was effected over this line by standard 250-watt equipment, and that this fact was witnessed by a number of persons interested in the subject. The quality of the talk and the ratio of noise to signal was such as to offer no opportunity for criticism.

In the design of equipment for power-line communication, I have always felt that simplicity, strength, and electrical stability were of utmost importance. For this reason I have always advocated the use of the simple system of modulation commonly used in broadcasting stations, and the use of ample power to overcome line noises. We have adhered strictly to the two-frequency type of equipment because of its simplicity and stability. Our experience is that this class of apparatus does not get the kind of maintenance commonly given to commercial telephone equipment. For this reason only the simplest and most stable circuits and adjustments are advisable.

Our experience with power lines agrees exactly with the general views of the authors in that we have found that power lines afford a more or less uncertain medium for communication. Instead of changing our communication apparatus we have attacked the cause and provided corrective means to the lines. As a result of progress in the art of stabilizing power lines, we can now reduce a complex circuit to a relatively simple circuit. Equipment for doing this is now available. Under these conditions the simple equipment using standard methods of modulation which has been available for years, is entirely satisfactory.

In Fig. 1 are given some test data on a 110-kv. line. Sufficient details are not given to check these data. The value of attenuation for the 98-mi. line as read from curve *I* is about 3 T U at 70 kilocycles and 10 T U at 120 kilocycles. The rate of increase of attenuation with the frequency does not seem to agree with the values obtained from the Bureau of Standards tables. The value of 3 T U is less than half that obtained in similar tests.

It is stated in the paper that, "the present tendency seems to be so largely toward the use of condenser coupling that it is scarcely necessary to discuss their respective merits." The present tendency toward the use of condensers rather than antennas is due largely to a technical misunderstanding regarding the electrical efficiency of the antenna type of coupling, which is commonly thought to be low. This view is in error as it can be shown that there is little practical difference in the over-all efficiency of either method. The selection of the type of coupling should be made with reference to mechanical rather than electrical considerations.

L. F. Fuller: I rather feel that the reduction in noise on the Pacific Gas & Electric System was effected very largely by the use of coupling capacitors. Whether the single side-band method caused a further material reduction or not, I do not know, but I think due credit should be given to the coupling capacitors for effecting a very substantial reduction as compared with the noise observed with the coupling wires.

All discussors of this paper, and Mr. Wolfe as well, have mentioned the desirability of stabilizing the attenuation characteristic of power lines. I want to point out that until such stabilizing is somewhat effected, we can hardly hope to crowd our narrow bands close together as we possibly would on a telephone line. We can hardly hope to take full advantage of the large number of channels which single side-band might permit, until the line itself, the transmitting medium, can be very materially improved.

Under "Initial Installation," the right-hand column, there is a sentence reading, "They have provided a communication service over power circuits which have presented very serious communication difficulties to other apparatus previously tried." The other apparatus, of course, was that of the General Electric and Westinghouse Companies.

In the interest of accuracy in the A. I. E. E. records, there is one fundamental point here that I should like to bring out. Mr. Wolfe pointed out that the actual setup involved the Claremont Substation, the Vaca Dixon Substation, and the Pit No. 1 Power House. One problem, of course, was by-passing or transferring signals around the transformers at Vaca. At the time that our apparatus was being tested, the Pacific Gas & Electric Company considered it desirable to couple on the line side of the oil breakers. However, when the equipment described by the authors was put into service, it was connected to the bus, and I believe it is now connected in that manner. That makes an entirely different problem. Mr. Jollyman mentioned in his discussion that connecting one 22-kv. line gave no detrimental result. I think that is obvious. You always have one good line or the other, unless both lines are off the bus, in which case you have lost the carrier. But the switching of the heavy transformers on and off the carrier circuit does not occur except as a balanced operation. If they switch on one or two of the three banks, they are affecting the carrier circuit on both sides. I think that should be borne in mind in considering this whole matter.

H. T. Plumb: The simple fundamental carrier communication, where carrier and sidebands are transmitted over a transmission line, has been found to be pretty good, and there isn't much noise.

I have had a little connection with carrier work that was done on the system of the Utah Power & Light Company. About three years ago they installed two equipments, one at either end of their 132,000-volt three-circuit transmission line. After operating very satisfactorily for about two years and, so far as I have been able to learn, without any interruption of that communication, they decided to install further equipments, and they now have six equipments scattered over about 300 mi. of high-voltage transmission lines. Those equipments are very satisfactory in their performance. They occasionally have trouble with the automatic selector of the telephone, or something of that sort, but they do not have any major troubles and the system is exceedingly simple.

If you refer to Fig. 2 in this paper you will begin to see complexities creep in, and it will give you the reason why it is necessary to have so many jacks on the front of the switchboard to seek out those troubles. But if you will simplify your equipment, you will not have to hunt trouble to the same extent.

J. D. Sarros: Mr. Neuman's questions on line modulation have been answered in part by other discussion but several points on this subject brought up by Mr. Boddie will be discussed later.

A sentence in our paper under "Initial Installation" has apparently given rise to a misunderstanding. We mentioned "very serious communication difficulties to other apparatus previously tried" but had reference only to our equipment of which we tried three distinct systems: first, a carrier-transmitted system; second, a carrier-suppressed system; and third a single-sideband system.

In connection with these trials, the following points are of interest.

About two years ago we installed terminals of our then standard carrier-transmitted equipment at Claremont and Vaca-Dixon substation and at Pit No. 1 Power House. We had no difficulty in providing a first-class communication circuit between Claremont and Vaca-Dixon. We found it impossible, however, to extend this service over the 220-kv. lines to Pit No. 1 Power House because of the excessive noise conditions encountered. Taking the 220-kv. circuit alone we found that the signal and noise levels were approximately equal at the receiving end. What was more interesting, however, was that raising the transmitting level from about 1 to 50 watts did not improve the signal-to-noise ratio. In other words, the noise increased as the transmitting level was raised.

Because of this interesting phenomenon, we were granted permission by the power company to conduct further tests to discover the nature of this noise condition and devise means, if possible, for overcoming it. We built a special amplifier which was capable of delivering as much as 1100 watts of high-frequency energy into the antenna system. Our supposition that this was not ordinary line noise was confirmed. Increasing the transmitting level from 1 to 1100 watts did not improve the signal to noise ratio at the receiving end. For certain special set-ups of the power system, of course, conditions were not so serious. The noise, for instance, would be considerably lessened with one 220-kv. line disconnected because of the peculiarity of the antenna system, as will be discussed later.

The equipment was finally modified in the field into a single-sideband system with the result that a very satisfactory circuit was provided from Vaca-Dixon to Pit No. 1 Power House with the 220-kv. power system normal.

On the basis of this experimental demonstration and because of the distinct advantages, as pointed out in the paper, resulting from single-sideband transmission, it was decided to develop commercial equipment of this design for use in power-line carrier telephony. As Mr. Ilgenfritz has stated in his discussion, the superiority of the carrier-suppressed type of transmission in telephone practise is so marked that the carrier-transmitted type has been discontinued and is becoming obsolete.

Although line modulation due to corona has not yet had direct experimental proof, our tests, outlined above, indicate that corona modulation is very plausible and that single-sideband transmission will overcome the distortion and noise resulting from it. Even with no line modulation present, the use of a single sideband will give a 3 T U discrimination against ordinary line noise as compared with the ordinary carrier-transmitted system. There is also, as Mr. Wilkins points out in his discussion, additional discrimination because of the inherent selectivity in the single-sideband system. In our tests, higher transmitting levels when using a carrier transmitted system resulted in correspondingly higher noise levels at the receiving end. This and the fact that the use of a single sideband or the elimination of the carrier (a carrier-suppressed system was successfully tried at the same time) resulted in a satisfactory circuit, gave rise to the theory that corona is the cause of line modulation.

In a carrier-transmitted system, for ordinary modulation more than 50 per cent of the energy is concentrated in the carrier frequency. Assuming that corona is the cause of line modulation between the carrier frequency and the corona frequencies, it is easy to see that this carrier undergoes a decided distortion. Now, modulation is a function of the product of this carrier frequency and the modulating frequencies and therefore an increase in the carrier will increase this distortion and the consequent noise after the signal is demodulated. By eliminating this carrier from the line and restricting this distortion to the single sideband alone, it is obvious that the noise level is reduced since the carrier necessary for demodulation is a pure carrier supplied locally at the receiver. This, we believe, accounts for the fact that even with 1100 watts of transmitted carrier it was impossible to set up a commercial circuit.

As Dr. Fuller states, the use of coupling condensers, because of more efficient coupling, is responsible for a large reduction in the noise. It was impossible, in this case, because of the rotation of the power conductors as they approached the substation yard, to obtain efficient coupling by means of antenna wires. In any case, however, there is no question but the present tendency towards the use of condenser rather than antenna coupling is due to the greater efficiency, stability, flexibility, and better quality afforded by the use of concentrated capacity for coupling the terminal equipment to the power line.

As stated in the paper, our object is to provide the power people with stable, reliable communication circuits of good quality with a maximum of flexibility and a minimum of maintenance. For this reason Mr. Jollyman's discussion is both encouraging and gratifying, for it shows plainly that this equipment is meeting successfully each and every one of these specifications.

Carrier Telephone System for Short Toll Circuits

BY H. S. BLACK,[1] M. L. ALMQUIST,[2] and L. M. ILGENFRITZ[2]
Associate, A. I. E. E. Associate, A. I. E. E. Non-member

Synopsis.—This paper describes a new carrier telephone system which is designed for use in the telephone plant as a substitute for open-wire line construction for circuits of shorter lengths than have been economical heretofore. This system, which is known as the type D carrier telephone system, provides one additional talking circuit per pair of wires. The equipment is adapted to provide facilities quickly, and is capable of being moved readily from one location to another when temporary facilities are desired. The system employs a novel and original modulation circuit which is fully described.

INTRODUCTION

ONE of the important developments in telephone engineering during the last decade has been the practical application of high-frequency currents for the transmission of telephone and telegraph messages over circuits simultaneously carrying other traffic. For the transmission of speech by this method, the band comprising the frequency components in the voice of the speaker, which in the ordinary telephone circuit are transmitted by electrical currents of the same frequencies, is translated into a band of high-frequency currents. These high-frequency or "carrier" currents are above those transmitted by the ordinary voice-frequency channel, so may be sent over a pair of wires that is being used for the transmission of speech frequencies. At the receiving end, the bands of high-frequency currents are separated from each other and from the voice currents on the same pair of wires by electrical filters so that each delivers its message independently.

The first commercial installation of carrier telephone equipment was in 1918 between Baltimore and Pittsburgh. Engineering and installation of carrier systems have progressed steadily from this time on. In 1921 the status of the art was reported to the Institute by Messrs. Colpitts and Blackwell in a paper entitled *Carrier Current Telephony and Telegraphy*,[3] which gave the fundamentals of the carrier current art and described two carrier telephone systems which had been developed up to that time, the type *A* and the type *B*. This paper also included a bibliography of material which had appeared up to that date.

Further advances in the carrier telephone art resulted in the development of the type *C* carrier telephone system, which provides three telephone circuits or "channels" in addition to the voice-frequency facilities normally carried by a pair of wires. This system was described by Messrs. Affel, Demarest, and Green[4] at the recent June convention of the Institute in a paper entitled *Carrier Systems on Long Distance Telephone Lines*, and a bibliography was given of material which had appeared since the presentation of the paper by Messrs. Colpitts and Blackwell in 1921.

In the paper describing the type *C* carrier telephone system, it was shown how, by the development of this system, the field of use of carrier telephony on the longer circuits in the Bell System has been greatly extended. There has also appeared to be a considerable field of use for carrier telephony on the shorter open-wire toll circuits, that is, those ranging from about 50 miles in length upward. The technical requirements for a carrier system designed particularly for use on these shorter circuits are in some respects less severe than those for a system capable of operation over much greater distances. In view of the relatively large number of circuits of these shorter lengths in the telephone plant, it has been found desirable to develop a type of system particularly adapted to this field of application. The purpose of this paper is to describe this system, which is known as the type *D* carrier telephone system.

In order to provide a carrier system which would be sufficiently low in first cost and maintenance to effect economies when used in place of wire construction for these shorter circuits, special consideration has been given to reducing the amount of apparatus required to a minimum and at the same time providing a system of such stability that very little maintenance would be required. By making the system a single-channel system, that is, one which provides only one additional talking circuit per pair of wires, by employing comparatively low carrier frequencies, and by including several new design features it has been possible to realize this aim. The provision of only a single channel results in a simpler and less expensive design for the filters, the use of low carrier frequencies results in decreased line attenuation and reduces the cost of line transpositions and carrier loading which may be required, while the new design features are of such a nature as not only to simplify the apparatus but to increase the stability of the circuit as well. The complete equipment for each system terminal is assembled as a unit which is wired and tested at the factory before shipment, thereby reducing engineering and installation costs.

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[1] Systems Development Department, Bell Telephone Laboratories.

[2] Department of Development and Research, American Telephone and Telegraph Company.

[3] *Carrier Current Telephony and Telegraphy*, E. H. Colpitts and O. B. Blackwell, A. I. E. E. TRANS., Vol. 40, 1921, pp. 205-300.

[4] A.I.E.E. Quarterly TRANS., Vol. 47, No. 4, 1928, p. 1360.

Presented at Pacific Coast Convention of the A. I. E. E., Spokane, Wash., Aug. 28-31, 1928.

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GENERAL ARRANGEMENT AND FUNCTIONING OF SYSTEM

The type *D* carrier telephone system is a single-channel system employing two separate carrier frequencies, one for each direction of transmission. It is a carrier suppressed system, that is, the carrier frequency itself is not transmitted from one terminal to the other but is generated locally at each terminal, and only a single sideband, which is all that is needed in order to transmit the speech, is passed over the circuit.

The frequency range occupied by the type *D* system is indicated in Fig. 1. For transmission in one direction, the lower side-band of a carrier of 10.3 kilocycles is used, while for transmission in the opposite direction, the lower sideband of a carrier of 6.87 kilocycles is used. This frequency allocation was selected in order to obtain comparatively low carrier frequencies and at the same time to permit the system to be used on the same pole line with certain types of long-haul carrier systems.

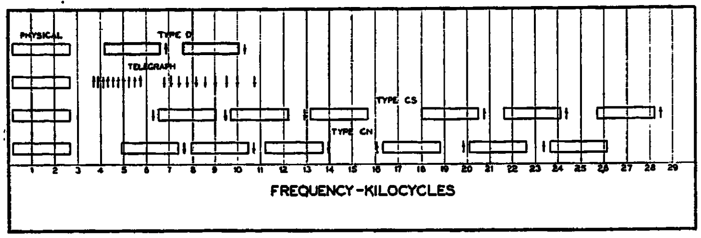

FIG. 1—FREQUENCY ALLOCATION OF TYPE D SYSTEM

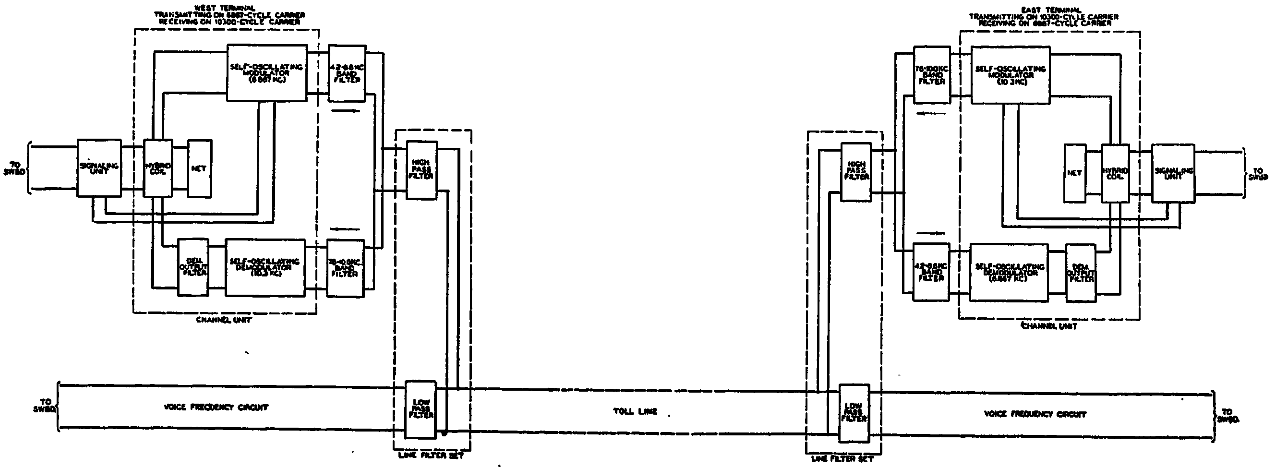

FIG. 2—LAYOUT OF BASIC TYPE D SYSTEM

The type *D* carrier telephone system has been provided in two general arrangements; the first employs certain basic equipment only and is suitable for operation over circuit lengths up to about 125 miles; the second employs the basic equipment together with terminal amplifiers and other additional equipment and is suitable for use on circuits up to about 200 miles in length. No provision is made for intermediate carrier repeaters as they are not required for the circuit lengths over which this system is designed to operate.

Basic Type D System. Fig. 2 shows in a general way the elementary features of the basic type *D* system. Referring to this figure, it will be noted that each terminal consists principally of a channel unit which comprises the modulator and demodulator and a hybrid coil to connect these two branches to a two-wire voice-frequency circuit, modulator and demodulator band filters to direct the carrier frequency currents into their proper paths, a line filter set consisting of high-pass and low-pass filters to provide separate paths for the voice and carrier currents which pass over the toll line, and a signaling unit to provide means for signaling over the carrier circuit. The channel unit also provides a demodulator output filter to suppress the high-frequency components in the output of the demodulator, and a network to balance the subscriber's line or other circuit to which the carrier system is connected.

The new electrical features which have been incorporated in this system consist principally of (1) the use of an arrangement whereby modulators and demodulators are self-oscillating, that is, the same vacuum tubes function both as oscillators and modulators or as oscillators and demodulators, thus economizing in the use of tubes and power, (2) the use of a new method of modulation and demodulation requiring the expenditure of a relatively small amount of plate battery power, (3) the elimination of grid batteries in the modulator and demodulator circuits by the use of grid current to produce grid biasing voltage, (4) the use of the modulator-oscillator circuit as a source of signaling current supply, and (5) the use of a ballast resistor to maintain the filament current within suitable limits. These new arrangements have resulted in economy in equipment as well as in a system of high stability. Economies also have been effected by the use of improved types of paper condensers in place of mica condensers in certain parts of the circuits, and by the use of unpotted coils where the requirements are such as to permit this to be done.

The general circuit arrangement is illustrated in greater detail in Fig. 3, which shows a schematic diagram of one terminal of the basic type *D* system. Carrier is produced by causing the tubes to oscillate in parallel, the frequency of the oscillations being controlled by the tuned circuit which couples the grid and plate circuits of the tubes. Speech currents from the switchboard pass into the hybrid coil, which functions both as hybrid coil and input transformer impressing the speech frequencies upon the grids of the modulator tubes. The application of these speech frequencies to the modulator, with the carrier frequency present, results in modulation, the principal products of which are the upper and lower side-bands. The desired grid biasing voltage is produced by the flow of rectified grid current through the resistance in the common lead of the grid circuits. By means of the balanced connection of the modulator output transformer, the carrier frequency is almost entirely suppressed and only a negligible amount appears in the output circuit. The output of the modulator passes to the modulator band filter where the upper sideband and other unwanted frequencies are suppressed and the lower sideband is permitted to pass on to the line through the high-pass line filter. The low-pass line filter prevents the high-frequency current from passing to a subscriber at the local terminal who may be talking on the voice-frequency line circuit on which the carrier is superimposed.

At the receiving terminal, the transmitted sideband passes through the high-pass line filter and the demodulator band filter to an input transformer which impresses it on the grids of the demodulator tubes. The application of these sideband frequencies to the demodulator, with the carrier frequency present, results in a reproduction of the voice frequencies applied at the sending end. Carrier and grid biasing voltage for the demodulator are obtained in the same manner as for the modulator. The various undesired high-frequency currents present in the output of the demodulator are suppressed by the low-pass filter in the output circuit. The voice currents are passed on to the hybrid coil and thence to the switchboard. The operation of these circuits is described in greater detail in the section on "Theory of Operation."

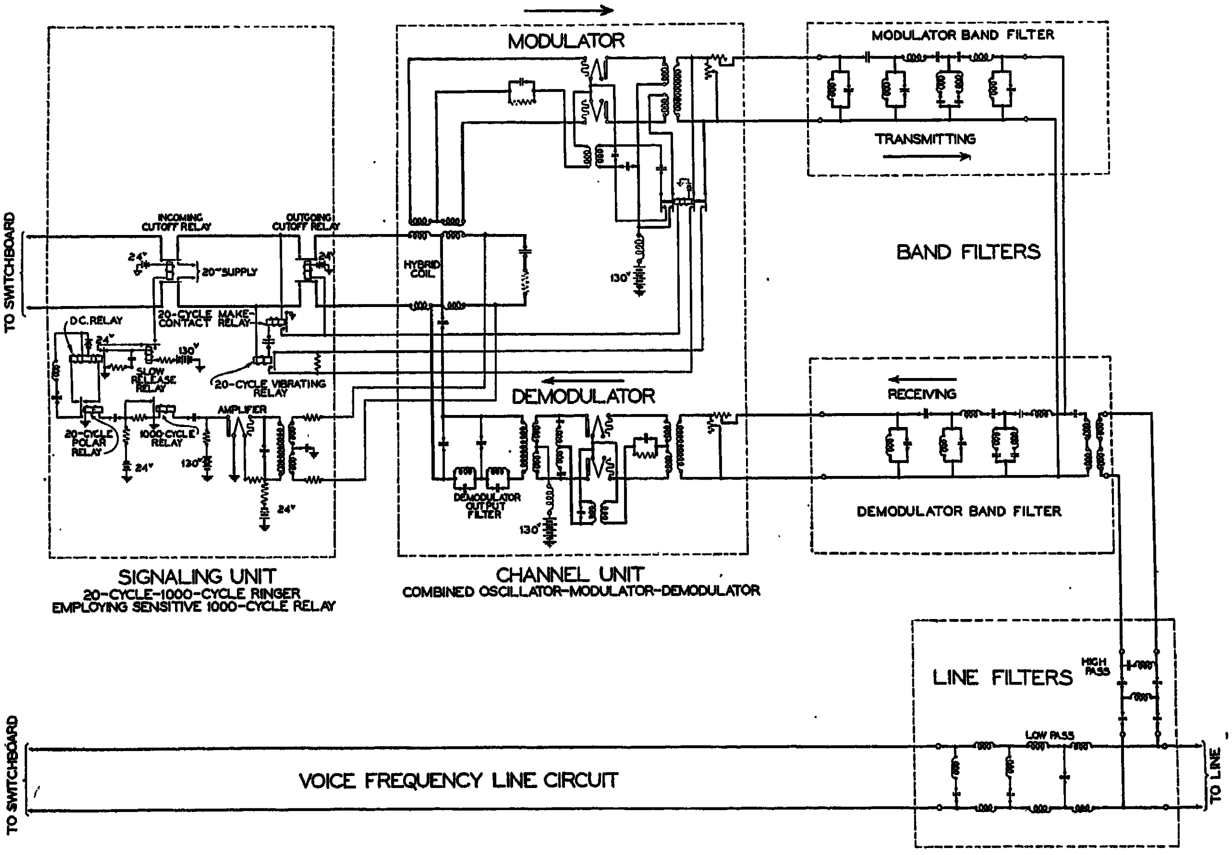

Fig. 3—Schematic of Terminal of Basic Type D System

The method provided for signaling over the carrier circuit is similar to that employed in the 1000-cycle signaling system used on wire circuits.[4] It differs in that signaling current is obtained by changing the connections of the modulator during the ringing period so that a separate source of 1000-cycle signaling current is not required. This arrangement is shown in Fig. 3. In order to signal over the carrier circuit, the modulator is unbalanced and the oscillator frequency reduced by 1000 cycles. The resulting high-frequency output is then interrupted at a 20-cycle rate. The receiving portion of the signaling circuit consists of an arrangement designed to respond to 1000-cycle current interrupted at a 20-cycle rate. The operation of the signaling equipment is described in more detail later.

Type D System with Terminal Amplifiers. The arrangement employing terminal amplifiers is known as the type *D-A* system, and is used where it is desired to cover the range of circuit lengths from about 125 miles up to about 200 miles. In addition it is used in some cases on circuits of shorter lengths in order to equalize transmission levels with respect to those of other carrier systems operating on the same pole line. This is necessary because the normal output levels of long-haul carrier systems are higher than those provided by the type *D* system without an amplifier. Also, certain circuit layouts involving only type *D* systems may require level equalization by the use of the amplifier.

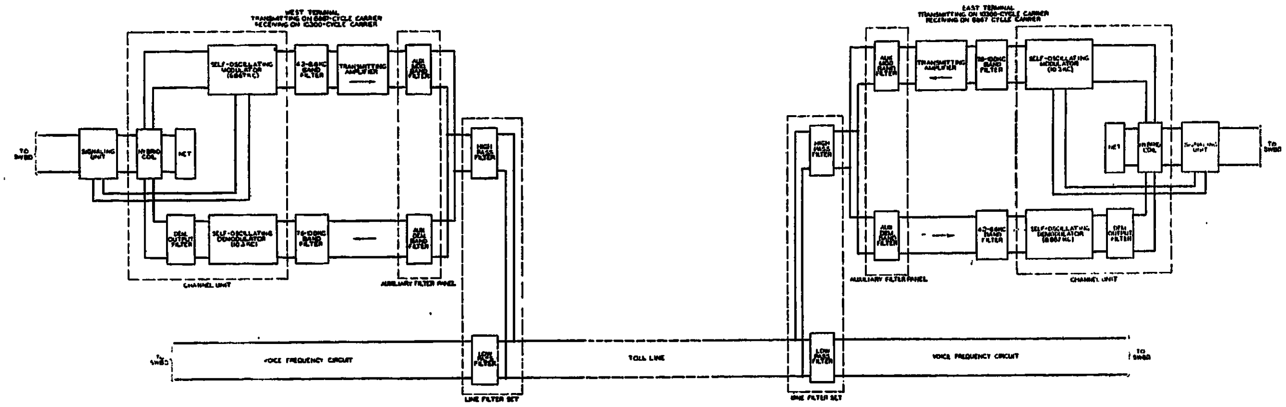

FIG. 4—LAYOUT OF TYPE D SYSTEM EMPLOYING TERMINAL AMPLIFIERS

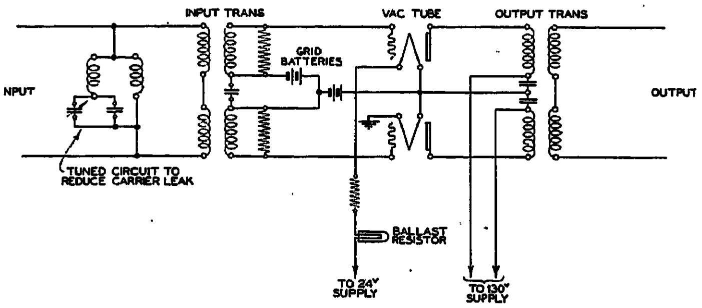

FIG. 5—SCHEMATIC OF AMPLIFIER CIRCUIT

Fig. 4 shows in a general way the elementary features of the type *D-A* system. It will be noted that the arrangement is similar to that for the basic type *D* system, the principal difference being the addition of an amplifier and a change in the design and arrangement of the band filters to provide additional selectivity.

The general circuit arrangement of the amplifier is shown in Fig. 5. It is a single stage, push-pull amplifier of conventional design, and has two tubes.

TRANSMISSION CONSIDERATIONS

In setting the transmission requirements for the type *D* system, it was first necessary to view the existing plant to see that other circuits would not be adversely affected by the use of this new type of facility, and to insure that it would provide transmission comparable with the latest standards of circuit performance.

Line Factors. Since the system was to be designed to operate over relatively short distances, it was important that it should be as simple and inexpensive as possible. It was necessary, therefore, to employ relatively low carrier frequencies in order that the amplification which the equipment would be required to provide should be comparatively low and the line stability good.

In many applications of the system no other types of carrier facilities will be operated on the same pole line, and in these cases there is no close restriction on the use of carrier frequencies above the normal voice range. There is also some demand for the application of these short systems on pole lines on which long-haul (type *C*) carrier telephone systems[4] and carrier telegraph systems[3] are operating. Therefore, bands were chosen in the lower carrier range which would permit operation on the same pole line with type *C* carrier telephone systems and carrier telegraph systems with a minimum of inter-system interference.

The two bands employed for transmission in the two directions have already been shown in Fig. 1. It will be noted that the lowest bands of the type *C-N* and type *D* systems are transmitted in opposite directions. As a result, since carrier transpositions are designed primarily to reduce far-end rather than near-end crosstalk between pairs on which carrier systems operate, as was explained in the recent paper on long-haul systems,[4] it will not be possible, in general, to operate type *D* systems on the same pole line with type *C-N* systems. Satisfactory operation can be obtained, however, with type *C-S* carrier telephone systems and carrier telegraph systems.

The difference in transmitting level between a basic type *D* system and a type *C* or a carrier telegraph system is rather large. To avoid excessive crosstalk from carrier telegraph systems into type *D* systems operated on the same pole line, it is necessary to use the type *D-A* system in order to obtain comparable levels. In certain unfavorable cases this will be necessary when type *C* systems are operated on the same line.

A comparatively inexpensive transposition system has been designed to permit the maximum number of type *D* systems to be operated on the same pole line. This system provides for the use of type *D* carrier systems on as many as four crossarms. When it is applied to lines on which no other type of carrier facility will be operated, it permits the use of basic type *D* systems on all pairs with the exception of the pole pairs. With slight modifications, it provides for the operation of two three-channel type *C-S* carrier telephone systems, one system on each of the outside phantom groups of the top arm, and, in addition, either a carrier telegraph or a type *D-A* carrier telephone system on the other pair of each of these phantom groups. Type *D-A* systems may also be operated on all other pairs of the line except on the pole pairs. Carrier telegraph systems can generally be operated on one or more of the pole pairs. The former transposition arrangement for the basic system, therefore, permits the operation of a total of 16 type *D* systems on a four-arm lead, and the latter arrangement with the long-haul systems permits the operation of two three-channel carrier telephone systems, 14 type *D-A* systems, and, in favorable cases, four ten-channel carrier telegraph systems on the same number of pairs, in addition to the grounded d-c. telegraph and the telephone facilities ordinarily obtained. Fig. 6 illustrates the relative positions of these facilities on the four crossarms.

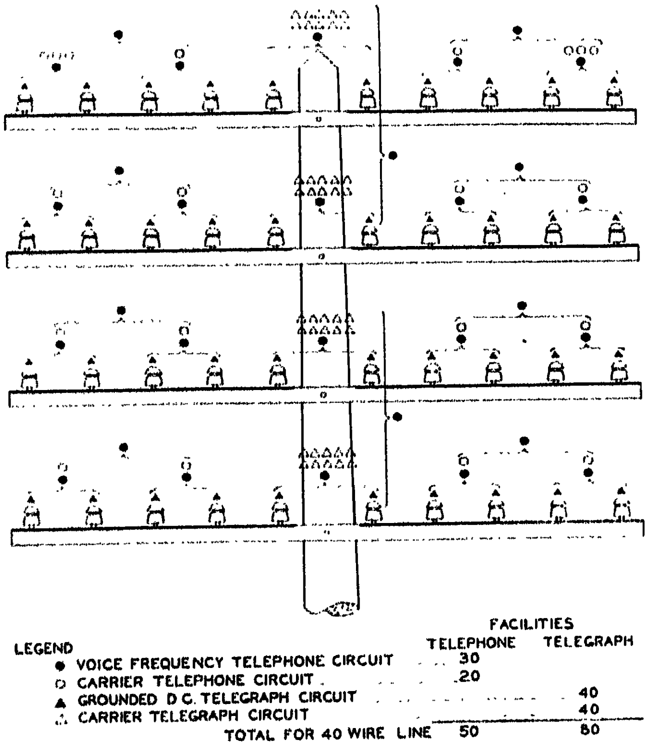
FACILITIES
LEGEND
TELEPHONE
TELEGRAPH
● VOICE FREQUENCY TELEPHONE CIRCUIT 30
○ CARRIER TELEPHONE CIRCUIT 20
▲ GROUNDED D C. TELEGRAPH CIRCUIT 40
△ CARRIER TELEGRAPH CIRCUIT 40
TOTAL FOR 40 WIRE LINE 50 80

Fig. 6—An Arrangement of Communication Facilities on Pole Line of Four Crossarms

In many of the open-wire circuits there are frequently included short sections of cable often aggregating several miles in length. When a number of systems is to be operated on the same pole line, it is generally necessary to load these sections of cable to avoid impedance irregularities and consequent reflection crosstalk. Loading may also be desirable in order to reduce reflection and cable attenuation losses in the line when only one or two systems are installed. An economical loading system has been developed to supply the demand in connection with type *D* systems. This same loading system may also be used for carrier telegraph systems, inasmuch as the frequency range employed is about the same. This loading system employs a coil spacing of about 3000 feet, roughly three times that of the design used for type *C* systems.

The office cabling in the runs between the line protectors, the distributing frames, and the various pieces of equipment in the circuit frequently adds up to considerable lengths and may introduce fairly large impedance irregularities. Consequently, there is need for a loading arrangement for the cabling in the larger offices. An economical loading system has been designed for the office wiring consisting of a loading coil and a pair of adjustable condensers. When comparatively short entrance cables are involved, these office loading units can be adjusted to load the office and entrance cable together.

Over-all Transmission Equivalent. At the comparatively low frequencies used and the short distances over which the system operates, the line losses are considerably less than at the higher frequencies used and the greater distances covered by channels of the type *C* system. The type *D* system will, if desired, provide a circuit of no greater equivalent than the voice frequency circuit on a 104-mil open-wire pair of the same length. The equipment for the basic system provides sufficient amplification to overcome line losses in excess of about six TU[5] for a 100-mile line, with an extra amplification allowance of four TU to overcome entrance or intermediate cable losses. The wet weather loss of 100 miles of 104-mil pair, which is the type of line on which the system will be operated in most cases, is approximately 12 TU at 10 kilocycles, which is about the highest frequency transmitted. Therefore, an aggregate amplification of approximatly 10 TU is desired in the sending and receiving circuits if a six TU equivalent is to be maintained. In cases involving negligible lengths of cable, the four TU amplification allowance can be used to extend the range of operation.

The distribution of this amplification between the transmitting and receiving circuits depends upon the noise on the line and the relative levels of other systems. Approximately six TU of amplification is obtained in the transmitting circuit, and the remaining four TU is obtained from the receiving circuit. Adjustments are provided in both circuits for changing these amplifications over certain ranges.

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[5] "The Transmission Unit," by R. V. L. Hartley, *Electrical Communication*, Vol. 3, No. 1, July 1924, p. 34; *Transmission Unit and Telephone Transmission Reference System*, by W. H. Martin, Trans. A. I. E. E., Vol. XLVIII, 1924, p. 797, *Bell System Tech. Jl.*, Vol. 3, July 1924, p. 400-408.

The equivalents are adjusted at the time of installation of the system by means of combinations of resistance networks in the modulator output and demodulator input circuits. These combinations of networks provide adjustments such that the overall equivalent may be brought within approximately 0.5 TU of the value desired for the circuit.

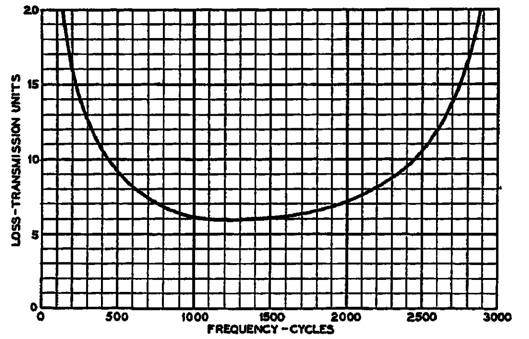

FIG. 7—REPRESENTATIVE SYSTEM TRANSMISSION FREQUENCY CHARACTERISTIC

Over-all Stability. It was considered very desirable to avoid the necessity for adjustments to compensate for changes in line loss and apparatus fluctuations either manually or automatically because of the cost of such control. The variations in line loss with weather at the frequencies employed by the type *D* system are much less than in the case of type *C* systems which operate at higher frequencies and over longer distances, and accordingly it appeared feasible to omit these adjustments, provided the equipment itself could be made sufficiently stable.

It was necessary, therefore, to insure a large degree of inherent stability in the design of the equipment so that apparatus for the adjustments of amplification, frequency, and filament current usually provided with carrier equipment might be omitted, thereby simplifying the system and reducing its cost.

The circuits have been so designed that the variations in the amplification and carrier frequency of the sending and receiving circuits with respect to normal fluctuations in power supply are negligible, and no compensating adjustments are required. The variations of transmitting and receiving amplification with plate battery fluctuations from 125 to 135 volts are not more than 0.1 TU. Variations in transmitting and receiving amplification with filament battery fluctuations from 20 to 28 volts are even less. Combined transmitting and receiving amplification changes with tube changes do not exceed approximately 1 TU. These are, however, of lesser importance as tubes are changed very infrequently.

The variations of high-frequency line equivalent are large in comparison with other variations in the system, although for the distances over which most of the systems operate these variations do not change the overall equivalent more than the usual maintenance limits. In the case of the systems approaching 200 miles in length, these limits may be slightly exceeded. However, the changes are apt to be of a seasonal character and may be corrected to some extent through the use of a pair of resistance networks controlled by a key.

Over-all Transmission Frequency Characteristics. Fig. 7 shows a representative transmission frequency characteristic. In general, the band transmitted by the type *D* system extends from about 200 cycles to 2700 cycles and is substantially the same for either direction of transmission.

The band is limited principally by the characteristics of the band filters, and variations in the transmission frequency characteristic are due largely to variations in manufacture of the filter elements. In some cases, the bands may be affected by irregularities in the line characteristic at the carrier frequencies, but these are caused by impedance reflections or absorption in the line and disappear when the lines have been properly prepared by loading and transposing.

Over-all System Load Capacity. In the design of the transmitting portion of the system, it has been necessary to provide for speech energy levels which are obtained directly from the toll switchboard. The demodulator load capacity may be somewhat less inasmuch as there will be a circuit equivalent or loss between the sending and receiving terminals. The load characteristic of a representative system as measured with 1000-cycle current is shown in Fig. 8.

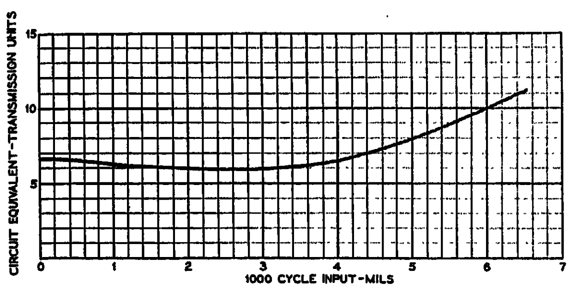

FIG. 8—REPRESENTATIVE SYSTEM LOAD CHARACTERISTIC

Impedance. It has been necessary to insure that the impedances of the equipment lie within satisfactory limits for a number of reasons. The impedance of the line filters has been made approximately the same as the average of the facilities over which the sytem will be operated. It is sufficiently uniform so that no serious impedance irregularities are introduced into the voice-frequency circuit on which the carrier system is superimposed. Any irregularities introduced by the filters would, of course, interfere with the balance obtainable at voice repeaters in the physical circuit at offices distant from the carrier terminals.

When a repeater in the physical circuit is located at a carrier terminal, the filter in the line is balanced by another filter in the network of the repeater, and the impedance of these filters must be similar in order that good balance may be obtained. For use in these cases, pairs of filters are selected at the factory to meet this requirement. This is considerably more economical than to manufacture each filter element to extremely high precision.

The high-frequency impedance of the carrier terminal is held to fairly close limits in order to avoid undesirable reflection effects, thereby increasing the effectiveness of the carrier transposition layouts.

Frequency Stability of Carriers. It is, of course, essential that the transmitting and receiving carrier frequencies for each direction of transmission maintain a reasonable degree of synchronism. The stability of the transmitting and receiving carriers of this system has been made as high as practicable in order to eliminate the necessity for adjustments which otherwise would have to be made rather frequently. The plate and filament battery fluctuations have a negligible effect on the frequencies of these carriers. The frequency changes amount to less than one cycle for the normal voltage ranges in either case. The frequency changes due to tube replacements are somewhat larger, the maximum being of the order of two cycles, and may be in either direction.

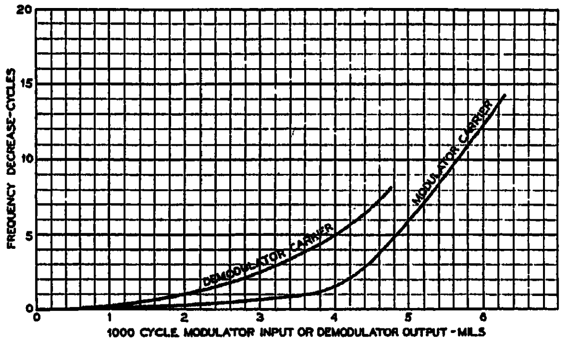

Fig. 9—Representative Variation of Carrier Frequency with Load

The carrier frequency decreases slightly with input load as shown in Fig. 9. This is peculiar to the particular type of circuit employed in this system. The change in transmitting carrier frequency is of the order of two cycles for single-frequency input currents up to four milliamperes into the hybrid coil, while that of the receiving carrier frequency is of the order of three cycles for output currents up to three milliamperes from the hybrid coil. Both changes are in the same direction so that the difference remains small. The speech currents transmitted will generally be much smaller than those mentioned above.

The largest frequency variations are due to temperature changes. These are illustrated in Fig. 10. The curves in this figure represent two extremes taken from a series of four oscillator-modulator circuits and four oscillator-demodulator circuits. A study of the variations of office temperature has shown that such variations will not cause the carrier frequencies at the two terminals to differ by more than about 20 cycles. Due to the comparatively low carrier frequencies employed, it has been possible to use relatively inexpensive paper condensers in the oscillator circuit and still obtain a satisfactory degree of stability.

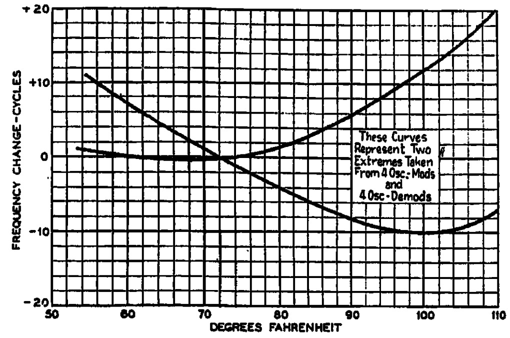

Fig. 10—Representative Variation of Carrier Frequency with Temperature

Filters. A line filter set has been designed particularly for use with the type *D* system. This line filter set is connected into the circuit on the office side of the telegraph composite set. It will, of course, introduce some loss in the voice-frequency circuit on which the carrier is operated.

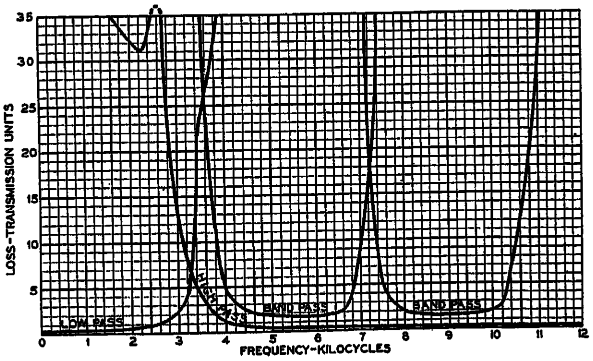

Fig. 11—Representative Filter Transmission Characteristics

The low-pass line filter is designed to suppress frequencies above approximately 2800 cycles. The characteristic of this filter is shown in Fig. 11. In this figure it will be noted that at 1000 cycles the filter introduces a loss of about 0.5 TU, this loss increasing slowly with frequency up to the cutoff point. Since such a filter is put in the circuit at each end, the net effect of the superposition of the carrier system is to introduce a loss of about one TU into the voice-frequency circuit.

The modulator and demodulator band filters have been designed to provide selectivity as economically as possible, that is, they offer selectivity only at those frequencies at which it is necessary in order to avoid interference originating either within the system or from external sources. For economic reasons these filters are of the unbalanced type. In order to insure the proper degree of longitudinal balance with respect to the high-frequency line circuit, a transformer is inserted between the high-pass filter and the band filters. In general, the transmission-frequency characteristics of the channels are limited by the filter attenuation characteristics. These are shown in Fig. 11 for a representative set of filters.

Two complete sets of band filters have been designed, one for use with the basic type *D* system and the other for use with the type *D-A* system which employs amplifiers. The latter set of band filters has been split so that part of the selectivity is furnished on each side of the amplifier in order to keep the unwanted frequencies produced in the modulator from overloading the amplifier, and at the same time to provide satisfactory impedance.

Amplifier. The amplifier has been designed to provide a high degree of flexibility. Either *O* or *L* type[6] tubes may be used, the grid potential and plate impedance of the amplifier being adjustable to accommodate either type. No changes in the amplifier apparatus other than certain minor changes in the connections are necessary in making this substitution. The *O* tubes are used only where maximum transmitting levels are required and *L* tubes are used for all other purposes.

The advantage in using *L* tubes is due to their lower power consumption and to arrangements which permit the grid batteries to be omitted and voltage drop in the filament circuit to be used to supply grid potential, thereby eliminating the cost of supplying and maintaining grid batteries. A total transmitting amplification of as much as 20 TU can be employed if the amplifier is equipped with *O* tubes. The load capacity with *L* tubes is about four TU less, but the available gain is about 3.5 TU greater.

The stability of the amplifier with power supply and tube changes is such that variations due to these causes are entirely negligible.

It will be noted in Fig. 5, the schematic of the amplifier, that an adjustable tuned circuit has been provided at the input. This is to suppress any carrier current which is present in the output of the modulator circuit so that the amplifier will not produce too much carrier current on the high-frequency line. Carrier current on the high-frequency line is objectionable from the standpoint of interference into dissimilar types of carrier systems.

Tests and Adjustments. The design and arrangement of the type *D* equipment are such that but little testing and adjustment are ordinarily required at the time of installation, and the high degree of stability in performance makes but little subsequent adjustment necessary. The performance of each type *D* terminal is tested before shipment from the factory. After the installation work has been completed it is necessary only to check the wiring and make initial adjustments before placing the system in service.

The initial adjustments made in the field consist of a synchronization of the carrier frequencies at the two terminals, and an adjustment to give the desired circuit equivalent. The adjustment of the circuit equivalent is made by means of resistance networks provided with the units, and is more or less permanent. Other tests and adjustments required are largely of the sort encountered in the installation and maintenance of ordinary telephone apparatus and are not such as to require frequent attention.

EQUIPMENT FEATURES AND TYPICAL INSTALLATIONS

In the design of new types of telephone equipment, it is important that the arrangements which are provided should be such that the new equipment will fit in readily with other telephone plant, and that it will apply to as wide a variety of plant conditions as practicable with little change in form. Care has been taken in the development of type *D* carrier telephone equipment to meet these requirements.

Assembly arrangements have been provided to meet the different office conditions. These are adapted for association with the other terminal room equipment. The circuit arrangement of the system is such that it does not require changes in the various types of switchboards with which it may be associated. From an operating standpoint, the circuit introduces no feature requiring the operator to differentiate between it and any other circuit. In these respects, the system is similar to other types of carrier systems.

Equipment for Basic Type D System. The equipment comprising each terminal of the basic type *D* system is shown in Fig. 12. It consists of five principal units, namely, the signaling unit, channel unit, modulator band filter, demodulator band filter, and line filter set. These are associated with jacks in such a way as to permit such testing and patching as may be required.

The apparatus for each of these units is assembled on a panel 19 in. wide and of sufficient height to provide the required mounting space. These panels are

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[6] The approximate characteristics of the *L* and *O* tubes employed in this system are as follows:

Type	Filament voltage	Filament current	Plate potential	Average plate current	Grid potential	Voltage amplification factor	Output impedance
L	4.5 v.	.97 amp.	130 v.	8 mils.	− 9 v.	5.9	5500 ohms
O	4.5 v.	.97 amp.	130 v.	23 mils.	− 22 v.	2.5	2000 ohms

mounted on a rack and wired together, the leads which go to points outside of the bay being wired to a terminal block located at the top of the rack. At the time of installation, wiring is provided from this terminal block to a central point known as the intermediate distributing frame (designated *I. D. F.* in Fig. 12), where connection is made to the particular toll line desired and to the switchboard.

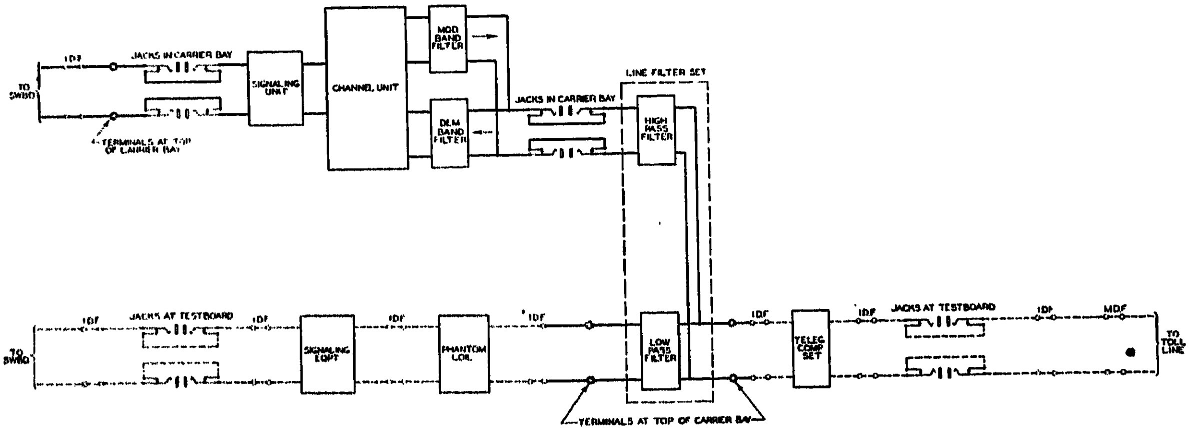

FIG. 12—SCHEMATIC OF TERMINAL OF BASIC TYPE D SYSTEM

Showing principal equipment units and method of connection to toll line

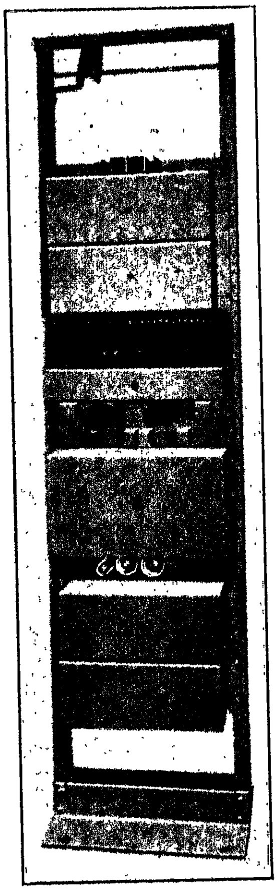

FIG. 13—TYPICAL ASSEMBLY OF TYPE D CARRIER TERMINAL ON FLOOR MOUNTED RACK

A typical assembly of a type *D* carrier terminal is shown in Fig. 13. This arrangement employs a floor mounted rack approximately seven feet high and includes all of the equipment comprising the carrier terminal with the exception of the power supply. The two box-like units near the bottom of the rack are the band filters. Directly above the band filters are the channel unit, signaling unit, adjusting unit, and jack panel, in the order named. Above the jack panel are the line filters and certain balancing equipment which is required when voice repeaters are used on the voice-frequency circuit on which the carrier system is superimposed, or on the circuit obtained by the carrier system. The adjusting unit comprises an arrangement to simplify adjustment of the 20-cycle polar relay used in the receiving part of the signaling circuit. This particular assembly arrangement is of advantage in temporary installations and in offices of low ceiling heights.

Where greater economy in floor space is desired, an assembly which provides the equipment for two type *D* carrier terminals on a rack 11½ feet high is used. The installation at Cedar Rapids, Ia., which consists of four type *D* terminals mounted in this manner is shown in Fig. 14. In this particular case, three bays instead of two were used as the installation consisted of three "east" terminals and one "west" terminal.

For each of these arrangements, the equipment is assembled on the rack and wired and tested at the factory as a complete unit, thereby reducing the time and work required for installation in the plant. The wiring required at installation consists only in cabling from the terminal block at the top of the bay to the distributing frame and to the sources of power supply.

The individual panels have been designed with a view to making the equipment as compact as possible. The modulator and demodulator apparatus, comprising the sending and receiving elements of the system, is mounted on one panel. This panel includes in one unit employing four vacuum tubes, the functions requiring two panels and six vacuum tubes in the long-haul carrier telephone equipment. The reduction in size has been due in part to the omission of adjusting apparatus, such as potentiometers. Such adjustments as are required are provided by soldered connections. This arrangement has proved satisfactory as the circuit is sufficiently stable so that these adjustments need be changed only occasionally. Fig. 15 shows a front view, and Fig. 16 a rear view, of the channel unit with the equipment covers removed, and illustrate the method of assembly and wiring used for this equipment. The equipment required for signaling is mounted on a separate panel, a front view of which is shown in Fig. 17. The filters are completely enclosed in copper containers which are sealed at the factory. This is done in order to provide sufficient shielding to permit the filters for different systems to be mounted in close proximity to each other. These containers are similar in form to the equipment covers which have been employed heretofore.

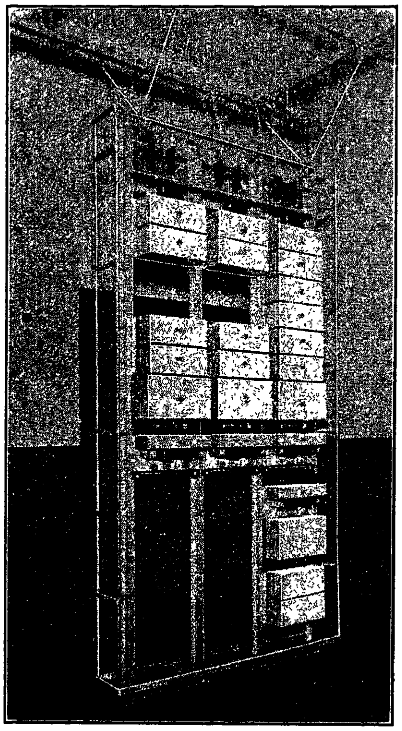
Fig. 14—Installation of Type D Carrier Terminals on High Type Racks at Cedar Rapids, Ia.

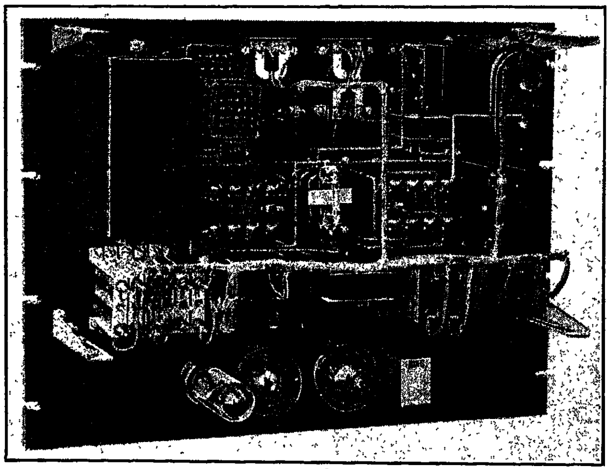
Fig. 15—Front View of Channel Unit with Cover Removed

Equipment for Type D-A System. The equipment for the type *D-A* system is the same as for the basic type *D* system except that an amplifier and an auxiliary band filter have been added and different band filters used. A typical assembly of a type *D-A* carrier terminal is shown in Fig. 18. This arrangement includes on one rack all of the equipment comprising the carrier terminal with the exception of power supply. The amplifier is located above the jack panel, and the auxiliary band filter directly above the amplifier. A front view of the amplifier panel is shown in Fig. 19. As in the case of the basic type *D* system, the equipment is assembled on the rack and wired and tested at the factory.

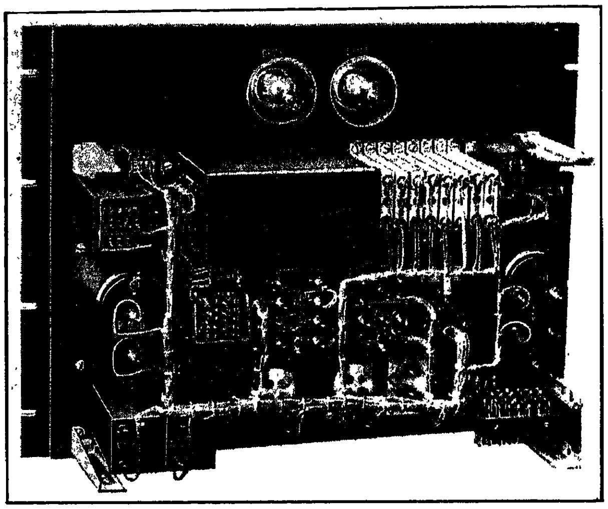
Fig. 16—Rear View of Channel Unit with Cover Removed

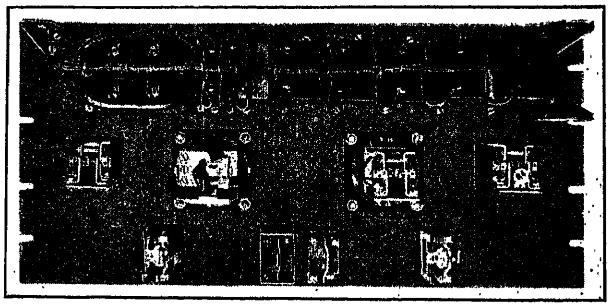
Fig. 17—Front View of Signaling Unit with Equipment Cover and Relay Covers Removed

Where a number of type *D-A* systems is to be installed in one office and economy in floor space is important, a slightly different arrangement from that illustrated above may be used. The equipment for two systems, with the exception of the line filters and balancing equipment, may be mounted on an 11½-ft.

rack, and the line filters and balancing equipment for a number of systems mounted together on a separate rack.

Equipment Quantities and Space Required. From the description of the assembly arrangements, it will be seen that the total amount of equipment for the two terminals of a basic type *D* system, exclusive of power supply, involves about 14 panels which may be assembled in space equivalent to about one bay,[7] occupying a total floor space, including aisle space, of about six square feet. If the channel which the system provides were obtained by wire circuits, the only office equipment required in general would be the phantom repeating coils, signaling equipment, and in some cases a telephone repeater, involving on the average only a small part of one bay. Thus, the furnishing of facilities by means of carrier while reducing the amount of outside plant required, considerably increases the space requirements for the inside plant.

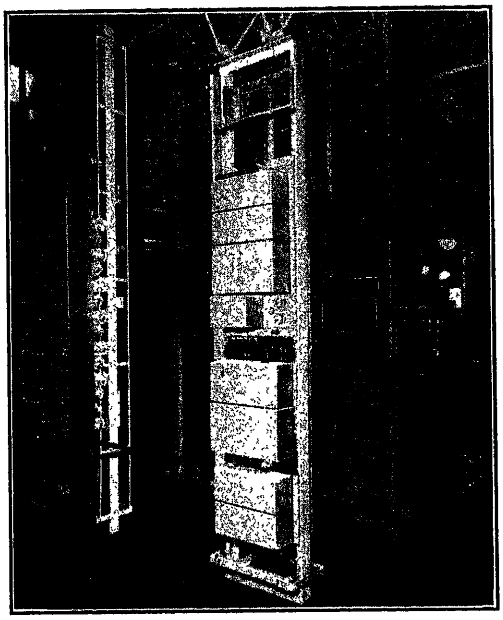

Fig. 18—Installation of Type D-A Carrier Terminal at Omaha, Neb.

In the case of the type *D-A* system, the total equipment per system is about 30 per cent greater. The corresponding wire circuit in most cases would include a telephone repeater.

Power Supply. The total power required for the two terminals of the basic type *D* system is in the neighborhood of two amperes at 24 volts, and 40 milliamperes at 130 volts. This corresponds roughly to the amount of power consumed by four telephone repeaters employing tubes requiring one ampere of filament current. For the type *D-A* system, additional power is required for the amplifier. This amounts to one ampere of filament current and about 16 milliamperes at 130 volts for plate supply at each terminal when *L* type tubes are employed, and one ampere of filament current and about 46 milliamperes for plate supply when *O* type tubes are employed.

It is frequently desired to install this carrier equipment in small telephone offices where adequate power supply is not available. In these cases, small 24-volt and 130-volt power plants, which have been developed recently, are used. These power supply units are of sufficient capacity to take care of several of the carrier systems. Each is assembled on a floor-mounted rack of the type employed for the type *D* equipment assemble shown in Fig. 13, and is so designed that it may be mounted adjacent to the carrier equipment when desired.

Adaptability to Establishing Service Quickly. An outstanding advantage of the type *D* system results from the features of its design and arrangement whereby the equipment for each terminal may be furnished as a complete self-contained unit requiring relatively little engineering and installation work. It is thus useful in providing facilities quickly, and is capable of being moved readily from one location to another where temporary facilities are involved. This has already proved to be an advantage of some importance to the telephone companies. A brief description of typical cases of this sort may be of interest.

The use of type *D* equipment played a prominent part in restoring telephone service in the New England flood area last November. A number of terminal equipments was just being completed in the factory when the flood occurred. In view of the emergency conditions, release of the equipment for five systems was obtained from the telephone company to whom it had been assigned, and immediate shipment made. These systems were installed and placed in service within a period of about two weeks under conditions which would not have permitted line construction. The location of these systems and the manner in which they were used in providing through circuits is shown in Fig. 20.

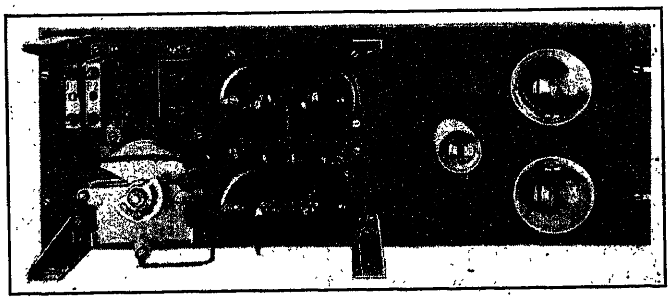

Fig. 19—Front View of Amplifier Panel with Cover Removed

Another instance in which the type *D* carrier telephone equipment served as a means of providing telephone facilities quickly under emergency conditions occurred last December. Due to a storm causing complete failure of the line between Syracuse and Watertown, New York, and partial failure of the circuits between Watertown and Utica, it was necessary to establish additional facilities on short notice. This was done by moving the Syracuse terminals of the two Syracuse-Watertown type *D* systems to Utica, thereby providing additional Watertown-Utica circuits which could be used to build up connections to Syracuse and other points. The time required for disconnecting the equipment at Syracuse, transporting it to Utica, and reinstalling it in that office amounted to about 32 hours.

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[7] A bay consists of two channel or I-beam uprights, ordinarily about 11½ ft. high, arranged to mount panels 19 in. wide and of varying height.

There have also been cases in which type *D* equipment has been used to provide facilities required as a result of sudden growth in oil fields. One case of this kind occurred during the fall of 1926, when oil was discovered some 40 miles northeast of Amarillo, Texas. Within three weeks, oil companies and other enterprises had established temporary quarters in this locality, which was named Borger, and requested that telephone service be furnished. A temporary line providing one phantom group was built from Amarillo to this newly established town. It was evident that this would not hold the traffic and accordingly, plans were formulated to build a permanent lead. In the meantime, however, it was necessary to provide additional facilities and it was decided to install a type *D* carrier telephone system. Two weeks from the date of shipment of the equipment, an additional talking circuit was provided between Amarillo and Borger with this carrier system.

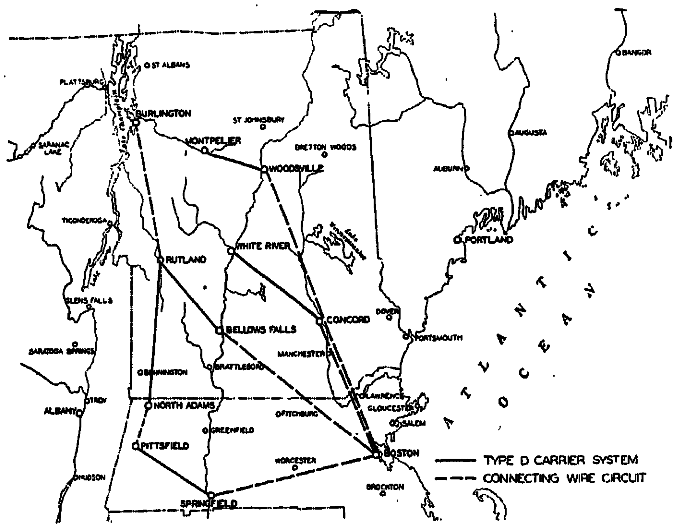

FIG. 20—LAYOUT OF CIRCUITS EMPLOYING TYPE D CARRIER SYSTEMS

Provided to meet emergency conditions in flood area in New England

After about 14 months, the oil activities at Borger were shifted to Panhandle, Texas. The toll traffic at Borger did not continue to justify the facilities that had been provided between this point and Amarillo. As traffic had increased between Pandhandle and Amarillo, Texas, the terminal of the type *D* carrier telephone system was removed from Borger and reinstalled in the Panhandle office, thus providing an additional circuit to this point at a very small additional expense.

THEORY OF OPERATION

It is believed that the principles governing the design of the system, particularly the modulator and demodulator units, because of their unique functioning, may be of interest to some readers. The following additional theoretical discussion and information is therefore offered.

Self-Oscillating Modulator. Aside from improved stability, important theoretical differences between this modulator and modulators employed previously in carrier systems are the combining of the functions of modulation and carrier generation, the replacement of grid biasing batteries by a grid resistance and capacity, and the use of a new method or type of modulation requiring the expenditure of only a very small amount of plate battery power.

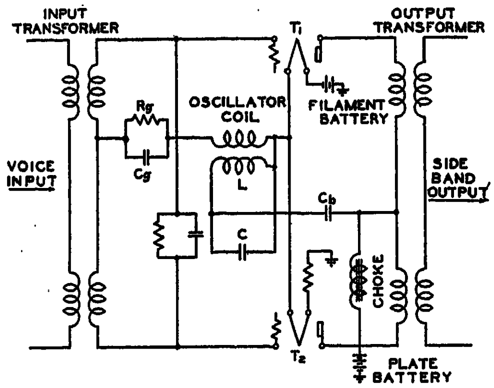

FIG. 21—SELF-OSCILLATING MODULATOR. CARRIER SUPPRESSED

Fig. 21 is a schematic of a self-oscillating push-pull modulator of this type. It is designed to suppress the carrier from the output. The self-oscillating modulator of Fig. 21 may be separately excited by an oscillator as shown by Fig. 22. Measurements have demonstrated that if other conditions are unchanged, the modulator amplification and load carrying capacity of both circuits are substantially identical as indicated by Fig. 23.

The generation of carrier frequency oscillations is accomplished by causing the two tubes to oscillate in parallel, the potentials of both grids being alike and rising and falling together at a rate corresponding to the carrier frequency. The input and output transformers offer negligible impedance to the carrier frequency oscillations because the impedance of the transformer windings parallel-opposing is very small. This low impedance to the carrier is important in connection with the stability of the oscillator in that any variations in the leakage inductance and distributed capacities of the transformer windings with temperature or time are required to have a negligible effect upon the frequency of the oscillations. The operation of the self-oscillating modulator as an oscillator is shown by Fig. 24, the oscillator of this figure being equivalent as regards the generation of oscillations to the self-oscillating modulator of Fig. 21.

The substantially constant grid biasing voltage applied to the grids of the oscillator tubes of Fig. 24 is obtained by rectifying in the grid circuit a portion of the sinusoidal carrier wave applied to the grids. The values of grid resistance, R_g, and grid capacity, C_g, are proportioned so that the grid biasing voltage obtained in this manner approaches closely the peak voltage of the applied carrier wave. The unidirectional conducting path from the grid to the filament functions as a two-element rectifier in the usual way. The quantity of electricity stored by the condenser, C_g, remains substantially constant. Referring to Fig. 25, during the discharge interval, t_d, the total condenser charge is diminished exponentially by a relatively small amount, the extent of the reduction depending upon R_g and C_g. During the charging interval, t_c, the grid is positive with respect to the filament and the total quantity of electricity stored in the condenser C_g is slightly increased. The relatively small quantity of electricity, ΔQ, discharged by the grid condenser and dissipated by the grid resistance during the discharge interval must equal the differential increment of quantity accumulated by the condenser during the charging interval. The portion of the wave rectified may be made as small as desired by making either R_g or C_g or both R_g and C_g sufficiently large. The constants of the circuit have been proportioned so as to rectify only a small portion of the wave. Fig. 25 represents the relation of the static characteristic of the tubes to the applied grid voltages. The constant grid biasing voltage applied to each of the two oscillator tubes of Fig. 24 differ by an amount corresponding to the voltage drop across the filament of a single tube owing to the series

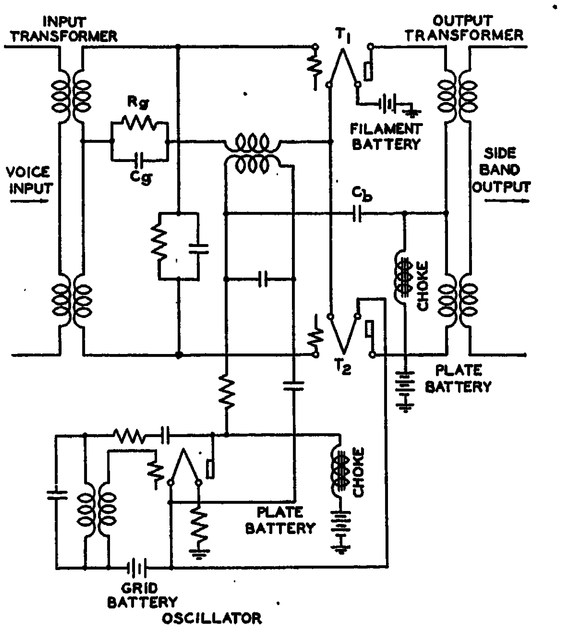

Fig. 22—Separately Excited Modulator. Carrier Suppressed

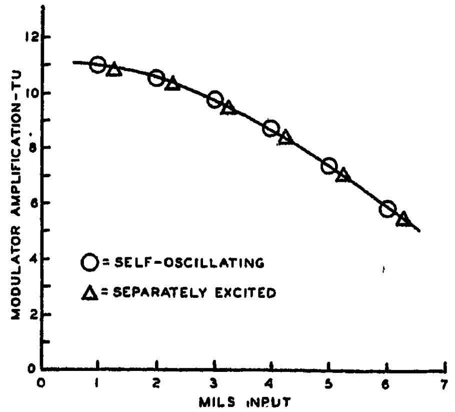

Fig. 23—Amplification and Load Characteristics of a Separately Excited Modulator Compared to a Similar Self-Oscillating Modulator

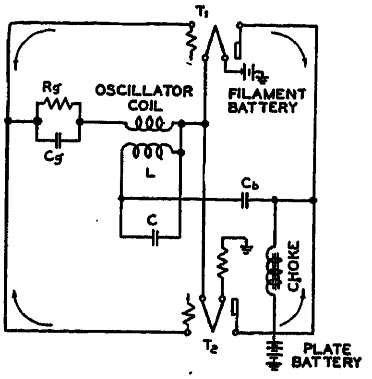

Fig. 24—Equivalent Oscillator Circuit of the Self-Oscillating Modulator of Fig. 21

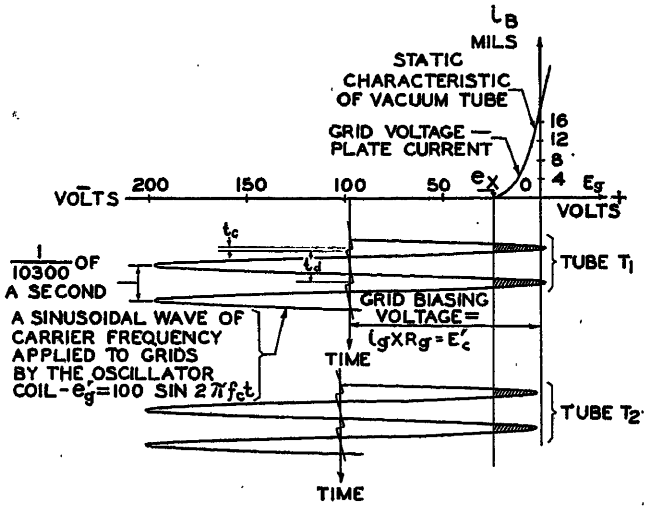
iB MILS
STATIC CHARACTERISTIC OF VACUUM TUBE
GRID VOLTAGE — PLATE CURRENT
16
12
8
4
VOLTS
200
150
100
50
ex
0
Eg +
VOLTS
tc
td
1/10300 OF A SECOND
TUBE T1
GRID BIASING VOLTAGE= igXRg=E'c
A SINUSOIDAL WAVE OF CARRIER FREQUENCY APPLIED TO GRIDS BY THE OSCILLATOR COIL-eg=100 SIN 2πfct
TIME
TUBE T2
TIME

Fig. 25—Relation of the Tube Characteristic to the Grid Voltages in the Oscillator of either Fig. 21 or Fig. 24. No Speech Input

connection of the filaments and the use of a common grid biasing circuit. This together with the fact that the portion of the carrier wave rectified is exceedingly small explains why, with no speech input, the grid of only one tube, T_1, is driven positive.

For the self-oscillating modulator of Fig. 21, Fig. 26 represents to a close approximation the relation of the static characteristic of the tubes to the constant grid biasing voltage and the varying voltage of the carrier wave, each applied to the two grids in parallel, assuming no speech input. A convenient method for computing and studying the characteristics of the self-oscillating modulator of Fig. 21 is merely an extension of a scheme of analysis first suggested by John R. Carson.[8] The assumptions involved in this method of analysis are shown by Fig. 27. In Fig. 28, the actual grid biasing voltage, E_c', and applied grid voltage, e_g', of the self-oscillating modulator are replaced by a fictitious grid biasing voltage, $E_c = e_x - E_{dc}$, and a fictitious grid voltage, e_g. These fictitious voltages produce substantially the same effects in the plate circuits as the actually applied voltages and simultaneously permit fulfilling the assumptions imposed by this method of analysis.

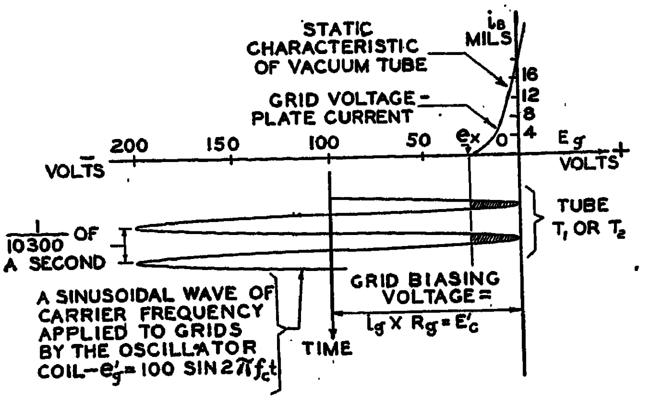
STATIC CHARACTERISTIC OF VACUUM TUBE
i_B MILS
16
12
8
4
GRID VOLTAGE-PLATE CURRENT
200
150
100
50
e_x
0
E_g
VOLTS
VOLTS
TUBE T_1 OR T_2
$\frac{1}{10300}$ OF A SECOND
A SINUSOIDAL WAVE OF CARRIER FREQUENCY APPLIED TO GRIDS BY THE OSCILLATOR COIL—$e_g' = 100 \sin 2\pi f_c t$
GRID BIASING VOLTAGE = $I_g \times R_g = E_c'$
TIME

Fig. 26—Approximate Relation of the Tube Characteristic to the Grid Voltage in the Self-Oscillating Modulator of Fig. 21. No Speech Input

While variations in the voltage amplification factor of the tube, μ, do not influence appreciably the production of oscillations and sideband in the self-oscillating modulator of Fig. 21, the effect of this additional variable might have been included in the analysis in a way similar to that suggested by Mr. F. B. Llewellyn.[9]

In considering the operation of the self-oscillating modulator as an oscillator, after the steady oscillations have been established, the attenuation around the closed oscillator circuit equals the amplification. Assume e_g' of Fig. 28 to be the steady-state voltage applied to the two grids in parallel. This voltage is substantially sinusoidal because the plate winding, L, of the oscillator coil is sharply tuned to the carrier or oscillator frequency. The grid biasing voltage, E_c', approaches the peak value of the alternating voltage applied to the grids. The grid voltages, E_c' and e_g', may be replaced by fictitious voltages, E_c and e_g, as previously explained. The alternating voltage, e_g, is amplified and distorted by the tubes and causes periodic pulses of current to flow in the plate circuit. The closed circuit $L\ C$ is only slightly damped and hence the current flowing in it induces in the secondary or high impedance winding of the oscillator coil a voltage in which the tuned or fundamental frequency predomi-

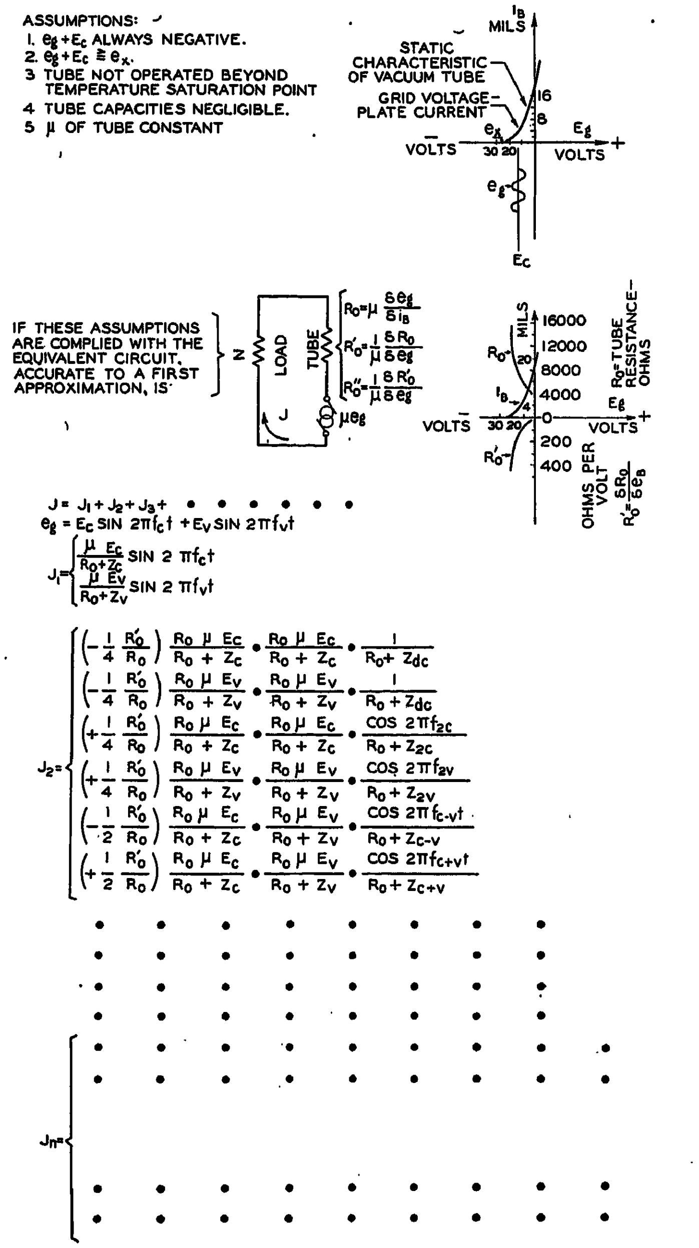
ASSUMPTIONS:
1. $e_g + E_c$ ALWAYS NEGATIVE.
2. $e_g + E_c \leq e_x$.
3 TUBE NOT OPERATED BEYOND TEMPERATURE SATURATION POINT
4 TUBE CAPACITIES NEGLIGIBLE.
5 μ OF TUBE CONSTANT
I_B MILS
STATIC CHARACTERISTIC OF VACUUM TUBE
GRID VOLTAGE-PLATE CURRENT
16
8
e_x
E_g
VOLTS
30 20
VOLTS
e_g
E_c
IF THESE ASSUMPTIONS ARE COMPLIED WITH THE EQUIVALENT CIRCUIT, ACCURATE TO A FIRST APPROXIMATION, IS
Z
LOAD
TUBE
J
μe_g
$R_0 = \mu \frac{\delta e_g}{\delta i_B}$
$R_0' = \frac{1}{\mu} \frac{\delta R_0}{\delta e_g}$
$R_0'' = \frac{1}{\mu} \frac{\delta R_0'}{\delta e_g}$
R_0
I_B
R_0'
MILS
16000
12000
8000
4000
0
200
400
VOLTS
30 20
E_g
VOLTS
R_0 = TUBE RESISTANCE—OHMS
OHMS PER VOLT
$R_0' = \frac{\delta R_0}{\delta e_B}$
$J = J_1 + J_2 + J_3 + \cdots$
$e_g = E_c \sin 2\pi f_c t + E_v \sin 2\pi f_v t$
$J_1 = \frac{\mu E_c}{R_0 + Z_c} \sin 2\pi f_c t$, $\frac{\mu E_v}{R_0 + Z_v} \sin 2\pi f_v t$
$J_2 = $
$\left(-\frac{1}{4}\frac{R_0'}{R_0}\right) \frac{R_0 \mu E_c}{R_0 + Z_c} \cdot \frac{R_0 \mu E_c}{R_0 + Z_c} \cdot \frac{1}{R_0 + Z_{dc}}$
$\left(-\frac{1}{4}\frac{R_0'}{R_0}\right) \frac{R_0 \mu E_v}{R_0 + Z_v} \cdot \frac{R_0 \mu E_v}{R_0 + Z_v} \cdot \frac{1}{R_0 + Z_{dc}}$
$\left(+\frac{1}{4}\frac{R_0'}{R_0}\right) \frac{R_0 \mu E_c}{R_0 + Z_c} \cdot \frac{R_0 \mu E_c}{R_0 + Z_c} \cdot \frac{\cos 2\pi f_{2c}}{R_0 + Z_{2c}}$
$\left(+\frac{1}{4}\frac{R_0'}{R_0}\right) \frac{R_0 \mu E_v}{R_0 + Z_v} \cdot \frac{R_0 \mu E_v}{R_0 + Z_v} \cdot \frac{\cos 2\pi f_{2v}}{R_0 + Z_{2v}}$
$\left(-\frac{1}{2}\frac{R_0'}{R_0}\right) \frac{R_0 \mu E_c}{R_0 + Z_c} \cdot \frac{R_0 \mu E_v}{R_0 + Z_v} \cdot \frac{\cos 2\pi f_{c-v} t}{R_0 + Z_{c-v}}$
$\left(+\frac{1}{2}\frac{R_0'}{R_0}\right) \frac{R_0 \mu E_c}{R_0 + Z_c} \cdot \frac{R_0 \mu E_v}{R_0 + Z_v} \cdot \frac{\cos 2\pi f_{c+v} t}{R_0 + Z_{c+v}}$
$J_n =$

Fig. 27—Theoretical Analysis Developed by John R. Carson

nates and which is the same as the assumed grid voltage, e_g'.

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[8] "Theory of Three-Electrode Vacuum Tube." *I. R. E. Proc.*, Vol. 7, April 1919, pp. 187-200.

"The Equivalent Circuit of the Vacuum Tube Modulator." *I. R. E. Proc.*, Vol. 9, June 1921, pp. 243-249.

"Notes on Theory of Modulation." *I. R. E. Proc.*, Vol. 10, February 1922, pp. 57-64.

[9] "Operation of Thermionic Vacuum Tube Circuits," *The Bell System Technical Journal*, Vol. 5, No. 3, July 1926, pp. 433-462.

The conditions for sustained oscillations are somewhat different from those of the ordinary type of oscillator since there is the possibility of the oscillations becoming intermittent unless this is prevented by an appropriate design of the circuit. As the oscillations are built up from a condition of rest they tend to increase until checked by some change in the circuit which results from their presence. In the ordinary oscillator this change, which may be an increase in the resistance of the plate path, for example, occurs simultaneously with the change in amplitude. In this circuit the increasing amplitude also causes a charge to accumulate on the condenser, C_g, with an accompanying increase in negative grid biasing voltage which tends to reduce the amplitude. The rate at which this charge leaks off (when left to itself) is an important factor in the maintenance of oscillations. Referring to Fig. 25, suppose that the rate at which the negative grid biasing voltage decreases during the interval, t_d, is decreased by increasing either R_g or C_g. The next pulse of current in the plate circuit will be less than its predecessor owing to the increased negative grid biasing voltage. Hence it will contribute less energy to the support of the oscillations in the circuit, $L\,C$, with the result that they will tend to decrease, which in turn will decrease the plate pulses and the energy supply for the oscillations. If this resultant rate of decrease in the amplitude of the alternating voltage applied to the grids is greater than the rate of change of grid biasing voltage, the process will continue until the oscillations cease. (Once the amplitude has fallen so that the grid no longer becomes positive at the peaks, no further increments of charge are given to C_g and the grid biasing voltage follows the continuous exponential discharge of the condenser). The discharge of C_g through R_g continues until the grid voltage is such as to permit a flow of plate current sufficient to start oscillations. When these reach the value of those present before the assumed change in R_g and C_g, the initial conditions will have been restored and the process will be repeated.

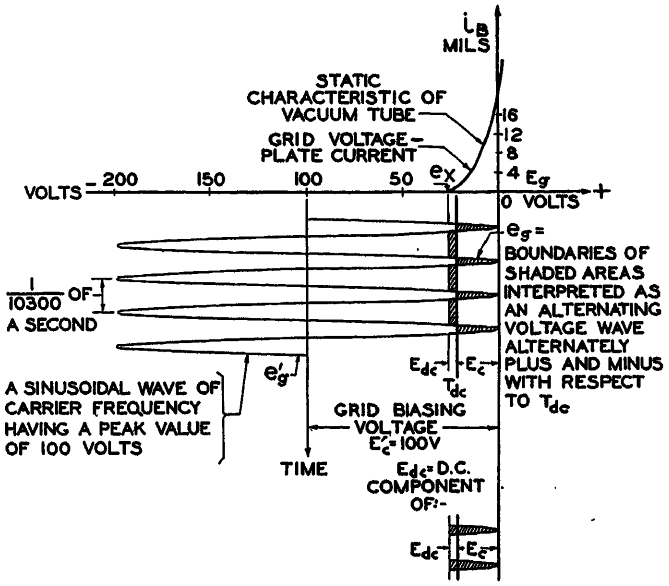
i_B MILS
STATIC CHARACTERISTIC OF VACUUM TUBE
GRID VOLTAGE-PLATE CURRENT
16
12
8
4
E_g
VOLTS
200
150
100
50
e_x
0 VOLTS
+
e_g = BOUNDARIES OF SHADED AREAS INTERPRETED AS AN ALTERNATING VOLTAGE WAVE ALTERNATELY PLUS AND MINUS WITH RESPECT TO T_{dc}
$\frac{1}{10300}$ OF A SECOND
A SINUSOIDAL WAVE OF CARRIER FREQUENCY HAVING A PEAK VALUE OF 100 VOLTS
e_g'
E_{dc}
E_c
T_{dc}
GRID BIASING VOLTAGE $E_c' = 100V$
TIME
E_{dc} = D.C. COMPONENT OF:-
E_{dc}
E_c

Fig. 28—Extension of Carson's Analysis to the Self-Oscillating Modulator. No Speech Input

The form of these intermittent oscillations is shown in Fig. 29, which is drawn from an oscillogram of the current through the condenser, C_g. However, the values of R_g and C_g at which the oscillations become intermittent can be increased by making the inductance of the choke coil in Fig. 24 large and the capacity of the condenser C_B reasonably small. At the end of a train of oscillations the plate current drops to zero and the negative grid biasing voltage exceeds the extinction voltage, e_x. As the grid biasing voltage follows the continuous exponential discharge of the condenser it slowly approaches and passes e_x, causing plate current to flow. The plate current continues to increase until after the start of the next train of high frequency oscillations. At the end of this train of oscillations the plate current drops again to zero. The frequency of the recurrent growth and decay of plate current corresponds to the relatively slow rate of occurrence of the spurts of oscillations. This low frequency current in the plate circuit is always present, if the circuit oscillates by spurts. If the plate circuit does not permit the presence of this low frequency current then this phenomenon can not take place. A large inductance choke coil and small by-pass condenser suppress the low frequency current necessary for this phenomenon by offering a high impedance to this current from the two plates of the two tubes in parallel to the filaments. From another point of view the effect of the choke coil and by-pass condenser may be considered as increasing the time constant of the oscillating circuit, $L\,C$.

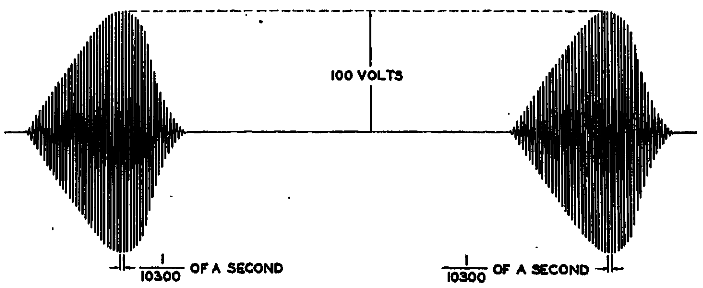

Fig. 29—Oscillation by Spurts

A large inductance choke coil and a small by-pass condenser likewise stabilize the carrier oscillations with heavy speech loads, even to an extent that otherwise would be impracticable of attainment. As an illustration of the effectiveness of this expedient, the use of a 180-henry choke coil increases the level or load carrying capacity of the self-oscillating modulator as gaged by articulation tests by more than six TU as compared to the performance with a choke coil having an inductance of 15 henrys.

A large inductance choke coil and a small by-pass condenser, serve indirectly to stabilize the frequency of the oscillations, since, by reducing the tendency of the circuit to oscillate by spurts, the grid resistance, R_g, and grid condenser, C_g, may be made larger than would otherwise be possible. Taking advantage of this will cause a reduction in the amount of energy dissipated in the grid circuit, thereby eliminating a number of variable factors which tend toward instability of the frequency of the oscillations. As an indication of the effectiveness of this scheme of control, if the condenser, C, in an oscillator similar to that of Fig. 24 is a high grade mica condenser having little energy dissipation, and the inductance, L, has but a slight amount of resistance, a change of plate battery voltage from 50 to 200 volts will cause a change in frequency of less than one part in a hundred thousand.

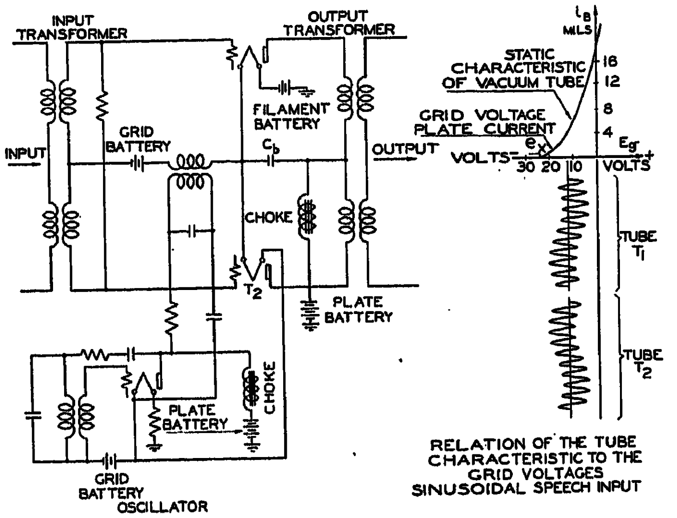

FIG. 30—CARSON TYPE OF PLATE CIRCUIT MODULATOR. CARRIER SUPPRESSED

Differences between the self-oscillating modulator of Fig. 21 and plate circuit modulators of the type described by John R. Carson and employed in former carrier systems are more readily emphasized by outlining briefly the operation of the older type of plate circuit modulator. Fig. 30 shows a modulator of this type together with the relationship of the static characteristic of the tube to the grid voltages. This circuit complies with the assumptions listed in Fig. 27 and hence the equations of this figure are suitable for evaluating the side-band current to a first approximation. The use of two tubes in a push-pull relationship does not sensibly alter the application of the equations, the use of two tubes instead of one serving to suppress the carrier and certain undesired higher order modulation products, and allow the carrier output impedance to be placed in a part of the circuit which is separate from the voice and sideband output impedances. The presence of sideband or new-frequency currents in this type of modulator is due to the sweeping of the voice and carrier voltages over the curved characteristic of the tube. The lower the load or output impedance to the carrier and voice-frequency currents, the greater will be the proportion of the amplified grid voltages available for sweeping over the tube characteristic, and consequently, the greater will be the output of the resulting sideband and other currents of new frequencies. The reason for this is that the sideband is proportional to the carrier and voice voltages. The carrier voltage, for example, is not the amplified carrier voltage, $\mu\ E_c$, but that portion of $\mu\ E_c$ that varies the plate current. Hence $\mu\ E_c$ must be reduced to take account of the external voltage drop around the plate circuit. As indicated by Fig. 27 the carrier voltage is $\mu\ E_c$ multiplied by $\frac{R_0}{R_0 + Z_c}$ and the corresponding voice voltage is $\mu\ E_v \frac{R_0}{R_0 + Z_v}$. In the push-pull modulator of Fig. 30 the carrier impedance Z_c depends upon the capacity, C_B, in the middle lead while the voice impedance is determined by the voice impedance looking into the high impedance winding of the output transformer, the low impedance winding being connected to the modulator band filter. If the alternating grid voltages are sufficiently small the assumptions previously referred to will be valid, and all higher order effects will be relatively unimportant. Under these conditions, maximum sideband power is obtained if the carrier impedance of the middle lead is zero, if the voice impedance across the high impedance side of the output transformer is zero, and if the impedance ratio of the output transformer is so adjusted as to make the load impedance connected to the tubes equal to the resistance of the tubes at frequencies corresponding to the sideband desired.

Attention is now directed toward certain properties of the Carson type of plate-circuit modulator which differ from corresponding properties of the self-oscillating modulator of Fig. 21. These properties are as follows:

1. The only grid voltages effective in varying the plate current are the impressed voice and carrier waves.
2. Modulation is present solely because of the curvature of the static characteristic of the tube.
3. The output impedances at frequencies corresponding to the voice, carrier, and side-band desired are for all practical purposes the only impedances effective in altering the sideband current, the impedance at all other frequencies being immaterial.

Keeping in mind the preceding explanation of the requirements for efficient production of new frequencies in the Carson type of plate-circuit modulator, an explanation of the reasons for the production of sideband in the self-oscillating modulator of Fig. 21 may be conveniently arrived at by analyzing only *that portion* of the applied sinusoidal grid voltages that is *effective* in varying the plate current. Fig. 31 indicates the approximate relation of the static characteristic of the tube to the constant grid biasing voltage and sinusoidal carrier and voice voltages applied to the grids. As before, energy dissipation in the grid circuit is slight and for the purpose of analysis it may be assumed that neither grid is driven positive, the effect of grid current on sideband production being negligible. Accordingly, the only alternating voltages existing in the grid circuit are the applied sinusoidal carrier and voice voltages, and furthermore, the constant grid biasing voltage closely equals the sum of the peak values of the voice and carrier voltages for the same reasons as were explained previously in describing the operation of the circuit as an oscillator with no speech input.[10] What happens in the plate circuit may be considered a result, the cause being a change in the grid voltage. Assuming that the extinction voltage, which is defined as the grid voltage for which the total instantaneous plate current is zero, is the static extinction voltage, e_x, Fig. 32 shows an indefinitely large number of new and fictitious sinusoidal grid voltages, which when taken together around a fictitious and smaller grid bias produce the identical result in the plate circuit as the two actually applied sinusoidal grid voltages and large grid bias.[11]

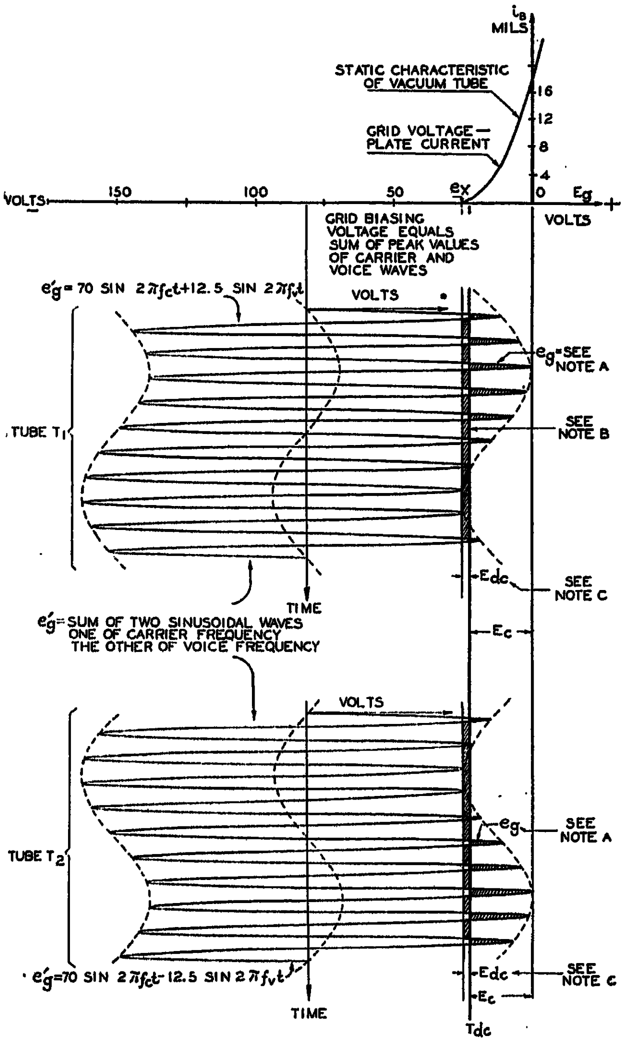

Fig. 31—Approximate Relation of the Tube Characteristic to the Grid Voltages in the Self-Oscillating Modulator of Fig. 21—Sinusoidal Speech Input

A. Boundaries of shaded areas interpreted as an alternating voltage wave, alternately plus and minus with respect to T_{dc}

B. The total instantaneous plate current is zero approximately 80 per cent of the time. If the output impedance is zero to all frequencies except the one sideband desired ($C - V$), at which frequencies the load impedance should be a pure resistance—then the total instantaneous plate current is zero whenever the negative grid voltage exceeds approximately 25 volts

C. D-c. component of boundaries of shaded areas

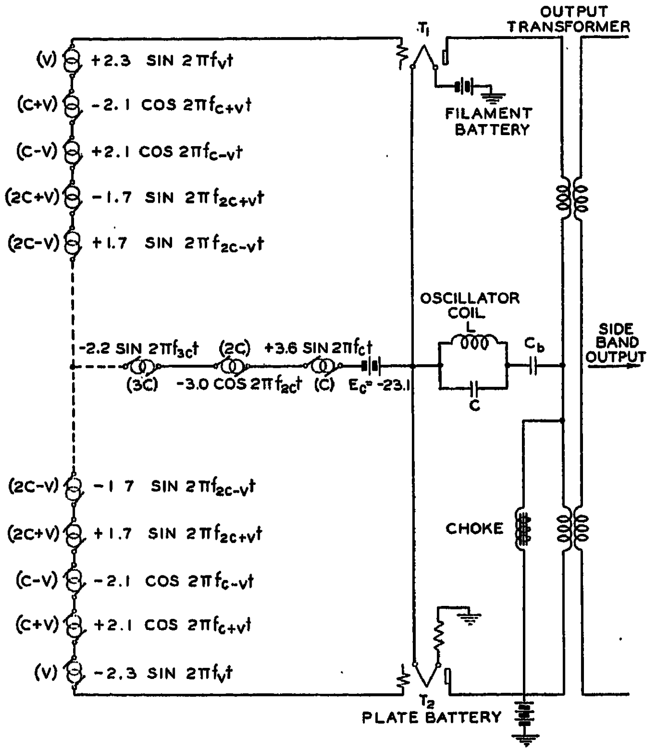

Fig. 32—A Diagram of Voltages which if Applied to the Grids as Shown Produce the Same Result in the Plate Circuit as the Carrier and Voice Voltages in the Modulator of Fig. 3

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[10] Whereas the grid biasing voltage equals the sum of the carrier and voice peaks, as explained, it should be understood clearly that the amplitude of the carrier oscillations will be unavoidably decreased as the speech increases. The presence of speech diminishes the amplitude of the oscillations by reducing that portion of the applied carrier voltage that is effective in varying the plate current.

[11] The extinction voltage is a function of the plate or load impedance. In this particular modulator, however, the *ideal* towards which the design of the output impedance should be directed is an impedance that is zero to *all* frequencies except the one sideband desired, at which frequencies the load impedance should be a pure resistance, and, for maximum power transfer, match the tubes at the operating point. Restricting the load impedance in this manner and simultaneously applying a relatively huge carrier voltage to the grids in parallel, causes the static and dynamic characteristics to approach coincidence as the applied voice voltage approaches zero. Even with heavy speech inputs, the static and dynamic extinction voltages may be assumed alike to a degree consistent with the equations of Fig. 27, which in turn are accurate only to a first approximation.

The result attained is exactly the same as if the sideband was produced as the result of a special scheme of double modulation employing two balanced modulators successively. In accordance with this scheme, the carrier and its harmonics together with the voice would be applied conjugately to the first modulator to yield in the two conjugate branches of the output of this modulator higher frequencies together with the voice, carrier, and sideband frequencies. By connecting the two conjugate branches of the output of the first modulator to the corresponding two conjugate branches of the input of the second modulator, the application of these new frequencies to the second modulator would then produce the sideband desired. The fact that in the self-oscillating modulator of Fig. 21 the only frequencies present in the grid circuit are the applied voice and carrier waves rather than the large number of fictitious frequencies indicated by Fig. 32 is fortunate, because otherwise impedance requirements that would be conflicting as well as difficult to meet would be imposed upon the input circuit. Suitable provision also would have to be made so that these frequencies could not find a path to the subscriber's subset. The self-oscillating modulator of Fig. 21 has all the advantages of the presence of a large number of higher frequencies in the grid circuit, and none of the disadvantages. Outstanding advantages are increased modulator amplification, improved stability, and a reduction in the plate current supplied by the plate battery.

Inasmuch as the sideband produced by the self-oscillating modulator of Figs. 21 and 31 is identical with that of the equivalent and more easily interpreted circuit of Fig. 32, the latter will be employed to describe the steps involved. The lower sideband is the modulation product desired, and this product, in preference to all other frequencies, is selected by the modulator band filter and transferred with slight attenuation to the line. The lower sideband is the result of five contributions,—one amplification and four modulations. One contribution is the amplification of $C-V$ which is one of the voltages present in the grid circuit of Fig. 32. Only a portion of the total sideband is contributed by modulation of carrier and voice due to the application of C and V to the grids, this phenomenon being identical with that in the Carson type of plate-circuit modulator of Fig. 30. The three remaining contributions to the lower sideband are modulations due to the application to the grids of three pairs of voltages, namely: C and $2C-V$; $2C$ and $C+V$; $3C$ and $2C+V$. The operation in each case is analagous to the Carson type of plate circuit modulator of Fig. 30, the carrier being replaced by C, $2C$, and $3C$ and the voice by $2C-V$, $C+V$, and $2C+V$ respectively. Assuming zero impedance in the common branch of the output circuit at the frequencies C, $2C$, and $3C$ and zero impedance plate to plate at frequencies corresponding to V, $C+V$, $2C+V$, and $2C-V$, then all five contributions are exactly in phase, fortunately, and add directly. Each of the sideband components produced by the four simultaneous modulations may be evaluated by suitably altering the equations of Fig. 27.

In this system the impedance in the middle lead or common branch of the output circuit approaches zero at the frequencies of the carrier and its harmonics. This end is attained by making the anti-resonant impedance of the oscillator coil low compared to the resistance, at the operating point, of the two tubes in parallel. The plate to plate impedance of the output circuit is caused to approach zero as compared to the resistance at the operating point of the tubes in series, at frequencies corresponding to V, $C+V$, and $2C-V$, and a pure resistance to the lower sideband of the carrier $C-V$. The plate to plate impedance of this particular modulator is relatively high at frequencies in excess of $2C+V$ because of the leakage inductance of the modulator output transformer and consequently additional possible contributions to the lower sideband are suppressed and therefore were not mentioned in the preceding discussion.

In designing the modulator, uniformity of performance under widely varying conditions was considered to be a very important ideal towards which the design of the circuit should be directed. The operation of the self-oscillating modulator in such a manner as described approaches this ideal because of the stabilizing or self-compensating properties of this particular type of circuit. To illustrate, anything having a tendency to cause the circuit to oscillate more violently and hence alter its properties as regards frequency of the oscillations, modulator amplification, or output impedance results simultaneously in an increase in the negative grid bias and changes the operating point on the tube characteristic, which effect, in turn, reduces slightly the amplitude of the oscillations and compensates to a high degree for what otherwise would have a tendency to alter to a considerable extent the properties of the circuit as a modulator. Compensation is equally effective irrespective of what circuit variable is tending to alter the performance. An idea as to the effectiveness of this type of control may be had by referring to Fig. 33, which indicates the stability of the more important characteristics of the self-oscillating modulator and represents results obtained with commercial equipment.

Self-Oscillating Demodulator. The operation of the demodulator, a schematic of which is shown in Fig. 3, is analogous to that of the modulator, the essential difference being that the signal frequency applied differentially to the grids of the demodulator is the lower sideband $C-V$ instead of the voice V as in the modulator. The former modulates with the locally generated carrier to yield in the demodulator output circuit the voice wave originally applied to the modulator at the distant or sending terminal.

The operation of the demodulator differs from that of the modulator in that the output impedance instead of being zero to all frequencies except the voice, is zero to the carrier but high to harmonics of the carrier, and zero to $C + V$ and $C - V$ but high to all other frequencies. This procedure has been followed, since, compared to the modulator, the demodulator should have a higher amplification although the load carrying capacity may be less. As an aid in attaining this end the peak voltage of the oscillations applied to the grids is 35 volts for the demodulator as compared to 100 volts for the modulator. The output impedance relationships are obtained by bridging two series tuned circuits across the high impedance winding of the voice-frequency demodulator output coil. Each circuit is broadly tuned to the carrier frequency and hence provides a low impedance path plate to plate at frequencies corresponding to $C + V$ and $C - V$, thereby increasing the efficiency of the demodulator. These tuned circuits also provide a convenient means for connecting the plates to the oscillator coil and condenser.

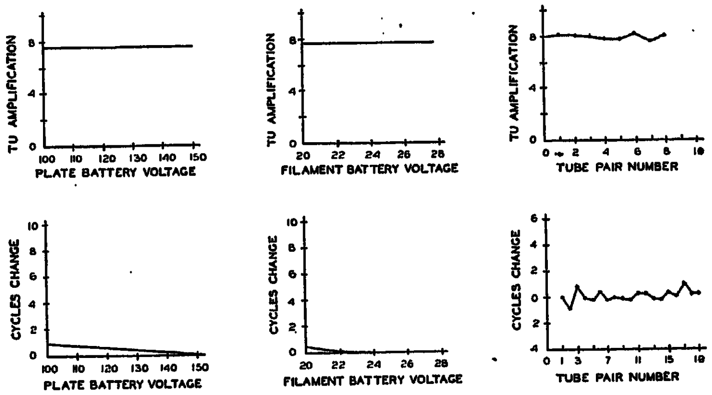

Fig. 33—Stability of the Self-Oscillating Modulator

Signaling. The method of signaling corresponds in general to voice-frequency signaling methods in current use on wire circuits with the exception that no separate source of 1000-cycle signaling current is required. Economy in power is obtained by the use of a sensitive alternating-current relay which, in effect, acts as a detector of 20-cycle modulation of 1000-cycle current. The sensitiveness of this relay permits a tube requiring only 60 milliamperes of current for filament operation to be used for amplifying the signaling current.

The signaling system is shown in schematic form in Fig. 3. Twenty-cycle ringing current from the toll switchboard is received by the signaling unit at the sending end, where it operates a relay chain. One relay in this chain connects an auxiliary condenser to the tuned circuit which controls the carrier frequency, thereby lowering the frequency of the carrier oscillations by 1000 cycles, and also unbalances the modulator by disconnecting plate battery from one of the tubes so that the carrier current is freely transmitted to the line. Simultaneously, another relay in this chain, the armature of which vibrates at a 20-cycle rate, short-circuits the output of the modulator twenty times a second. The net result of an outgoing 20-cycle signal from the switchboard is, therefore, to transmit modified carrier current interrupted at a 20-cycle rate over the line.

At the distant end the received carrier current differs by 1000 cycles from the demodulator carrier frequency, so it appears in the demodulator output as 1000-cycle current interrupted at a 20-cycle rate. This current after amplification operates a 1000-cycle relay. The input circuit of the amplifier is tuned to 1000 cycles to reduce the sensitivity to currents of other frequencies. The 1000-cycle relay follows the 20-cycle interruptions of the signaling current, that is, its armature vibrates at a 1000-cycle rate during the periods of approximately one-fortieth of a second that 1000-cycle current is applied, and remains at rest during the periods of approximately one-fortieth of a second that the current is interrupted. A set of contacts on this relay opens when the armature vibrates, so the net effect is that these contacts open and close at a 20-cycle rate.

A sensitive polar relay is associated with the contacts of the 1000-cycle relay in such a way that its armature vibrates at the rate at which the contacts on the 1000-cycle relay open and close. A direct-current relay and a 20-cycle tuned circuit consisting of a coil and condenser are associated with the contacts of this polar relay in such a way that when the armature of the polar relay is vibrating, the condenser in the tuned circuit alternately charges through one winding and discharges through a second winding of the direct-current relay. If the armature of the polar relay vibrates at a 20-cycle rate, the current flowing through the direct-current relay will be sufficient to cause it to operate. The tuning of the 20-cycle circuit is sufficiently sharp so that the direct-current relay will fail to operate if the armature of the polar relay vibrates at a rate differing from 20 cycles by more than a few cycles. This is an important factor in making the signaling equipment free from false operation from voice and other interfering currents.

When this direct-current relay has remained operated for approximately three-quarters of a second, it causes 20-cycle current to be sent to the switchboard, where it operates a relay which causes a visual signal to be given to the toll operator. This delay is controlled by a slow release relay, and is an additional safeguard to prevent false operation of the ringer, inasmuch as it requires that signaling current be applied for a specified length of time.

CONCLUSIONS

With the development of the type *D* carrier telephone system, the art of carrier telephony has been brought to the point where it can be used to advantage in providing telephone facilities for much shorter circuits than have been economical heretofore. Type *D* systems now in service are operating principally over distances of about

75 to 200 miles, although in certain cases where the conditions are favorable, systems as short as about 50 miles are in use. The exact distance beyond which it is more economical to employ this carrier system than to string additional wire, is, of course, dependent upon the conditions applying to each particular case. For greater distances, up to the limit of operation of the system, the economies effected by its use increase quite rapidly.

The performance of the type *D* system is comparable with that of a corresponding wire circuit. The form of the equipment is such that it is well adapted to the various office conditions, that it can be used to provide facilities quickly, and that it can be transferred readily from one location to another in case of emergency.

On June 1, 1928, approximately 125 type *D* carrier telephone systems were in service and operating satisfactorily. It is expected that by the end of 1928 the number of systems in use will have increased to about 225. The growth in short open-wire toll circuits is such that there is a considerable field of application for this system.

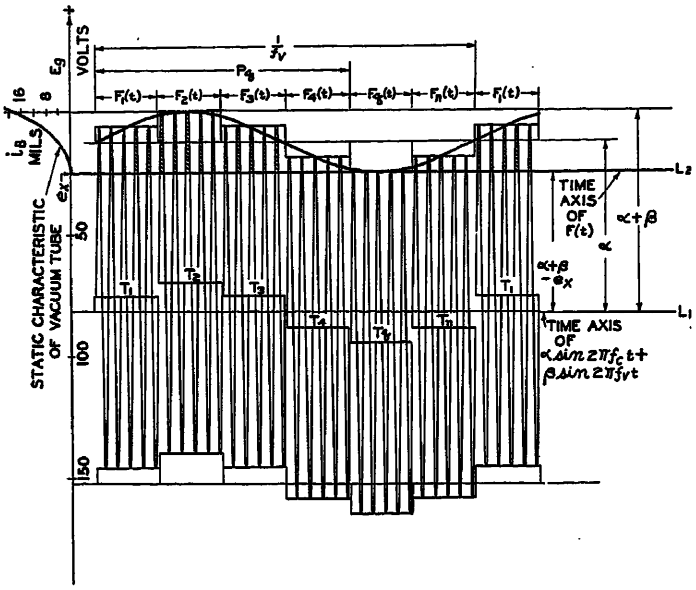

Fig. 34

Appendix

The mathematical treatment of the steps involved in the transition from Fig. 31 to Fig. 32 may not be evident, although this type of problem is frequently encountered in the theoretical analysis and design of vacuum tube circuits and analogous electrical systems. The problem may be stated as follows: *given,*—a complex wave which is the sum of two sinusoidal waves; *required,*—to express as a series of sine and cosine terms and a constant term, all having coefficients readily evaluated, that portion of the complex wave which lies above a line, parallel to the axis of the given wave and at a stipulated distance from it.[12]

$$\Phi(t) = \alpha \sin 2\pi f_c t + \beta \sin 2\pi f_v t^{13} \tag{1}$$

$\Phi(t)$ is the given complex wave. In addition the simplifying, although not essential, assumption is made that f_c and f_v are incommensurable.[14] Referring to Fig. 34, that portion of $\Phi(t)$ which is to be analyzed is denoted $F(t)$. $F(t)$ lies above line, L_2, which is parallel to line, L_1, the time axis of $\Phi(t)$ and at a distance $(\alpha + \beta - e_x)$ above it. Line, L_2, is taken as the time axis about which $F(t)$ is to be expanded. Fig. 34 is drawn for the special case in which $2\beta = e_x$; this does not in any way interfere with the generality of the equations.

The envelope of $F(t)$, Fig. 34, is a sinusoidal wave of period $1/f_v$, drawn about a line above, parallel to, and displaced from L_1 by an amount (α). This sinusoidal wave commencing with $t = 0$ and over an interval of time $1/f_v$ is divided into n parts, as shown by Fig. 34, by dividing $1/f_v$ into n equal increments of time and erecting ordinates. Remaining portions of the wave are divided similarly. The given function, $\Phi(t)$, is replaced by a new and different function which is the sum of n separate functions, the sum of the separate functions approaching $\Phi(t)$ as n increases without limit. As

$$n \doteq \infty, \Phi(t) \doteq \Phi_1(t) + \Phi_2(t) + \ldots \Phi_q(t) + \ldots \Phi_n(t)$$

where

$\Phi_1(t) = \alpha \sin 2\pi f_c t$ redrawn at recurrent intervals of time about T_1 as shown by Fig. 34

$\Phi_2(t) = \alpha \sin 2\pi f_c t$ redrawn at recurrent intervals of time about T_2 as shown by Fig. 34

. . . .

. . . .

$\Phi_q(t) = \alpha \sin 2\pi f_c t$ redrawn at recurrent intervals of time about T_q as shown by Fig. 34

. . . .

. . . .

$\Phi_n(t) = \alpha \sin 2\pi f_c t$ redrawn at recurrent intervals of time about T_n as shown by Fig. 34

and q denotes the system $1, 2, 3, \ldots\ldots n$.

---

[12] Theoretically, it is possible to write the solution of this problem as either a Fourier's Series or Integral depending upon whether or not the frequencies are commensurable. It is impracticable, however, to compute the coefficients of the various terms in the expansion of $\Phi(t)$ by direct use of the Fourier formulas because each coefficient is itself expressed as a sum of a very large number of terms.

[13] If the waves are commensurable the effect of phase displacement between the given sinusoidal waves may be taken into account by replacing (1) by $[\alpha \sin(2\pi f_c t + \Psi_1) + \beta \sin(2\pi f_v t + \Psi_2)]$ and modifying certain of the subsequent equations.

[14] This assumption simplifies the results sought by reducing greatly the number of terms of interest in the series and by making all terms independent of the particular numbers selected to represent the frequencies denoted f_c and f_v.

As $\Phi(t)$ defines $F(t)$ so by analogy $\Phi_1(t)$ defines $F_1(t)$; $\Phi_2(t)$, $F_2(t)$; . . . . $\Phi_q(t)$, $F_q(t)$ . . . . $\Phi_n(t)$, $F_n(t)$.

$$\text{As} \quad n \doteq \infty \quad F(t) \doteq \sum_{q=1}^{q=\infty} F_q(t) \tag{2}$$

Consider the function $F_1(t)$, Fig. 34. Let S_1, Fig. 35, denote the Fourier's series which would represent the shaded peaks of a wave of frequency f_c recurring from $t = -\infty$ to $t = +\infty$ at an amplitude equal to the amplitude of the peaks during the time intervals corresponding to T_1. Let U_1, Fig. 35, be the function which has the value unity during the time intervals corresponding to T_1, Fig. 34, and zero all remaining times.

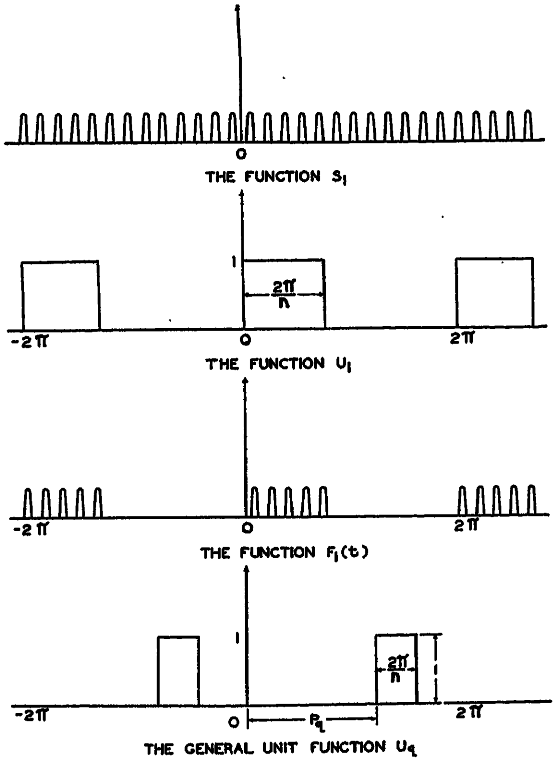

Fig. 35

$F_1(t) = S_1 U_1$ and as $n \doteq \infty$.

$$F(t) \doteq F_1(t) + F_2(t) + \ldots F_q(t) + \ldots F_n(t)$$
$$= S_1 U_1 + S_2 U_2 + \ldots S_q U_q + \ldots S_n U_n$$

Representing an approximation to the general unit function, U_q, of Fig. 35[15] by the Fourier's series:

$$U_q = \frac{1}{n} + \sum_{k=1}^{k=K} \frac{1}{k\pi} \left[\sin \frac{2\pi k}{n} \cos (2\pi f_{kv} t - k p_q) + \left(1 - \cos \frac{2\pi k}{n}\right) \sin (2\pi f_{kv} t - k p_q) \right] \tag{4}$$

where K is an arbitrary number which will eventually be made infinite.

Letting n increase without limit and replacing $\sin \frac{2\pi k}{n}$ by $\frac{2\pi k}{n}$ and $\cos \frac{2\pi k}{n}$ by 1, we obtain:

$$U_q = \frac{1}{n} + \frac{2}{n} \sum_{k=1}^{k=K} (\cos k p_q \cos 2\pi f_{kv} t + \sin k p_q \sin 2\pi f_{kv} t)^{16} \tag{5}$$

Representing S_q by the Fourier's series:

$$S_q = \left(\frac{B_0}{2}\right)_q + (A_1)_q \sin 2\pi f_c t - (B_2)_q \cos 2\pi f_{2c} t - (A_3)_q \sin 2\pi f_{3c} t + \ldots \tag{6}$$

The expression for $F(t)$ desired is obtained by multiplying Equations (5) and (6) term by term and noting terms of the form[17]

$$\left.\begin{aligned} \sum_{q=1}^{q=n} (B_m)_q \cos k p_q &= 0 \\ \sum_{q=1}^{q=n} (A_m)_q \cos k p_q &= 0 \end{aligned}\right\} \text{for } k \text{ odd}$$

and

$$\left.\begin{aligned} \sum_{q=1}^{q=n} (B_m)_q \sin k p_q &= 0 \\ \sum_{q=1}^{q=n} (A_m)_q \sin k p_q &= 0 \end{aligned}\right\} \text{for } k \text{ even}$$

Hence

$$F(t) = \left[\frac{1}{n} \sum_{q=1}^{q=n} \left(\frac{B_0}{2}\right)_q\right] + \left[\frac{1}{n} \sum_{q=1}^{q=n} (A_1)_q\right] \sin 2\pi f_c t - \left[\frac{1}{n} \sum_{q=1}^{q=n} (B_2)_q\right] \cos 2\pi f_{2c} t$$

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[15] In this and certain subsequent figures it has been found convenient to express the abscissa in terms of radians.

[16] Although the limiting form of this series is divergent it can be interpreted so as to be a valid representation of an infinitely narrow unit function.

[17] The particular symmetry of the coefficients, some of which are shown in Fig. 38, is a factor in causing these terms to vanish.

$$-\left[\frac{1}{n}\sum_{q=1}^{q=n}(A_3)_q\right]\sin 2\pi f_{3c}t + \ldots\ldots'$$

$$+2\left[\frac{1}{n}\sum_{q=1}^{q=n}\left(\frac{B_0}{2}\right)_q\sin p_q\right]\sin 2\pi f_v t$$

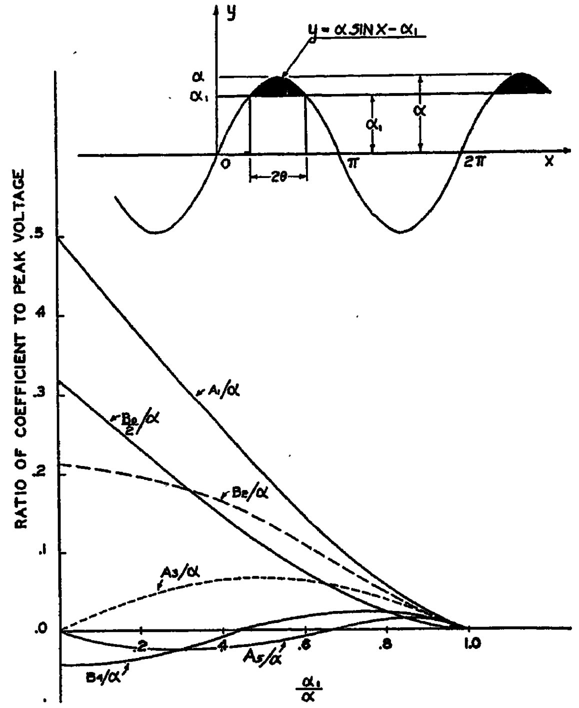

FIG. 36

$$+2\left[\frac{1}{n}\sum_{q=1}^{q=n}\left(\frac{B_0}{2}\right)_q\cos 2p_q\right]\cos 2\pi f_{2v}t$$

$$+\ldots\ldots$$

$$+\left[\frac{1}{n}\sum_{q=1}^{q=n}(A_1)_q\sin p_q\right]$$

$$(\cos 2\pi f_{c-v}t - \cos 2\pi f_{c+v}t)$$

$$+\left[\frac{1}{n}\sum_{q=1}^{q=n}(B_2)_q\sin p_q\right]$$

$$(\sin 2\pi f_{2c-v}t - \sin 2\pi f_{2c+v}t)$$

$$+\left[\frac{1}{n}\sum_{q=1}^{q=n}(A_3)_q\sin p_q\right]$$

$$(-\cos 2\pi f_{3c-v}t + \cos 2\pi f_{3c+v}t) + \ldots$$

$$+\left[\frac{1}{n}\sum_{q=1}^{q=n}(A_1)_q\cos 2p_q\right]$$

$$(-\sin 2\pi f_{c-2v}t + \sin 2\pi f_{c+2v}t) + \ldots$$

$$+\ldots\ldots\ldots\ldots \qquad (7)$$

All the coefficients of this series are arithmetical averages, taken over one cycle of the sinusoidal wave of frequency f_v. Each coefficient may be evaluated either analytically by integration or graphically by plotting the coefficient and determining the average value of the graph.

Illustrative Example. To illustrate the method, the operations which were performed to obtain a graphical solution in a particular case will be listed. For the sake of brevity, only the term of frequency $c - v$ will be considered, other terms being obtained in an analogous manner.

This term is $\left[\frac{1}{n}\sum_{q=1}^{q=n}(A_1)_q\sin p_q\right]\cos 2\pi f_{c-v}t.$

As a preliminary step in obtaining the graphical solutions, the coefficients of the series, S_q, are evaluated and plotted, Fig. 36

$$S_q = \left(\frac{B_0}{2}\right)_q + (A_1)_q\sin 2\pi f_c t - (B_2)_q\cos 2\pi f_{2c}t$$

$$- (A_3)_q\sin 2\pi f_{3c}t$$

$$+ (B_4)_q\cos 2\pi f_{4c}t + (A_5)_q\sin 2\pi f_{5c}t \ldots\ldots$$

$$\ldots + (-1)^{\frac{3m+1}{2}}(B_{m-1})_q\cos 2\pi f_{(m-1)c}t$$

$$+ (-1)^{\frac{3m+1}{2}}(A_m)_q\sin 2\pi f_{mc}t$$

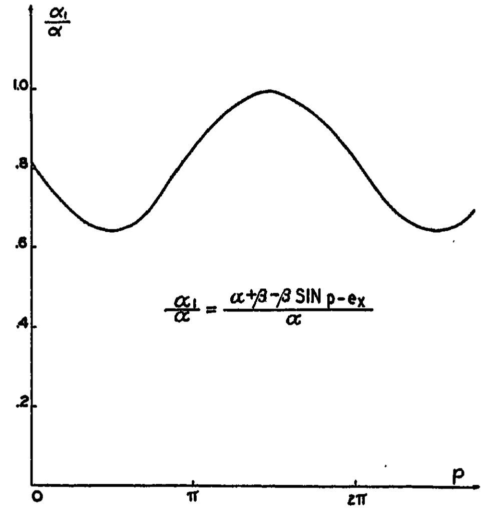

FIG. 37

$$\frac{B_0}{2} = \frac{\alpha}{\pi}\left[\sin\theta - \frac{\alpha_1}{\alpha}\theta\right]$$

$$A_1 = \frac{\alpha}{\pi}\left[\theta - \frac{2\alpha_1}{\alpha}\sin\theta + \frac{1}{2}\sin 2\theta\right]$$

$$B_2 = \frac{\alpha}{\pi}\left[\sin\theta - \frac{\alpha_1}{\alpha}\sin 2\theta + \frac{1}{3}\sin 3\theta\right]$$

$$A_3 = \frac{\alpha}{\pi}\left[\frac{1}{2}\sin 2\,\theta - \frac{2}{3}\frac{\alpha_1}{\alpha}\sin 3\,\theta + \frac{1}{4}\sin 4\,\theta\right]$$

$$B_4 = \frac{\alpha}{\pi}\left[\frac{1}{3}\sin 3\,\theta - \frac{2}{4}\frac{\alpha_1}{\alpha}\sin 4\,\theta + \frac{1}{5}\sin 5\,\theta\right]$$

$$A_5 = \frac{\alpha}{\pi}\left[\frac{1}{4}\sin 4\,\theta - \frac{2}{5}\frac{\alpha_1}{\alpha}\sin 5\,\theta + \frac{1}{6}\sin 6\,\theta\right]$$

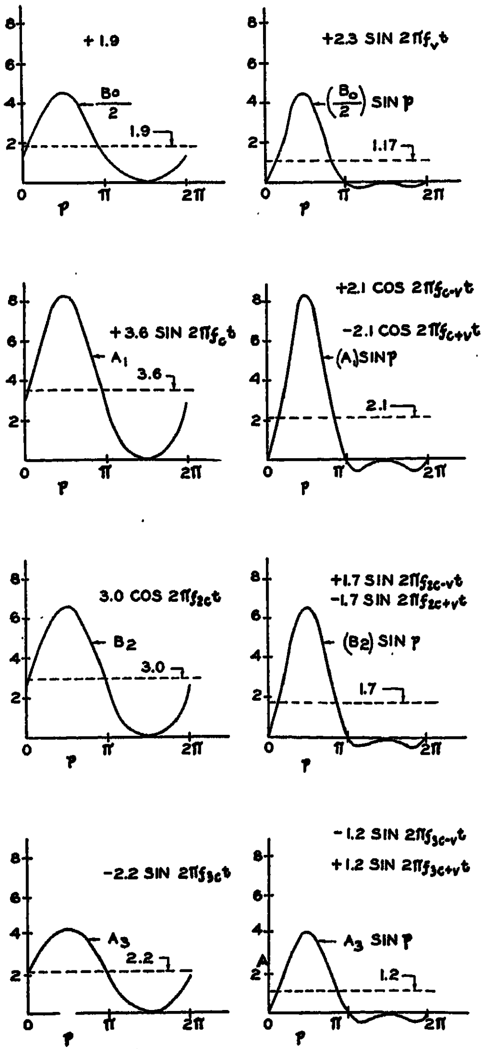

Fig. 38

. . . .

. . . .

$$B_{m-1} = (-1)^{\frac{3m+1}{2}}\frac{\alpha}{\pi}\left[\frac{1}{m-2}\sin(m-2)\,\theta - \frac{2\,\alpha_1}{\alpha(m-1)}\sin(m-1)\,\theta + \frac{1}{m}\sin m\,\theta\right]$$

$$A_m = (-1)^{\frac{3m+1}{2}}\frac{\alpha}{\pi}\left[\frac{1}{m-1}\sin(m-1)\,\theta - \frac{2}{\alpha}\frac{\alpha_1}{m}\sin m\,\theta + \frac{1}{m+1}\sin(m+1)\,\theta\right]$$

. . . .

. . . .

where m is odd and > 1.

As may be seen by referring to Fig. 36, the first six of these coefficients are plotted as a function of $\frac{\alpha_1}{\alpha}$ where $\frac{\alpha_1}{\alpha} = \cos\theta$.

From the equation $\frac{\alpha_1}{\alpha} = \frac{\alpha + \beta - e_x}{\alpha} - \frac{\beta}{\alpha}\sin p$, derived from the geometrical relationships of Fig. 34, $\frac{\alpha_1}{\alpha}$ is plotted as a function of p from $p = 0$ to $p = 2\,\pi$, Fig. 37. This and other functions of p which are plotted and shown by figures are periodic.

For each value of p may be determined the corresponding value of $\frac{\alpha_1}{\alpha}$, Fig. 37, and hence A_1, Fig. 36. Proceeding in this manner ($A_1 \sin p$), Fig. 38, may be plotted as a function of p. The average ordinate of this graph is the coefficient sought, namely

$$\left[\frac{1}{n}\sum_{q=1}^{q=n}(A_1)_q \sin p_q\right].$$

In Fig. 31, $\alpha = 70$, $\beta = 12.5$, and $e_x = 25$ volts. Employing these values of the constants, the coefficients of the terms shown in Fig. 32 may be evaluated as described. Fig. 38 shows graphs, the average values of which equal these various coefficients.

Discussion

M. L. Almquist: There are certain points in connection with the development of the equipment described in this paper which may be of interest.

In many cases, the short toll circuits to which the type *D* carrier telephone system is applicable connect small towns with the larger toll centers, so that there is a considerable use for this equipment in small offices. In these small offices it is particularly desirable that the installation and maintenance of the equipment should be as simple as possible. Due to its high inherent stability and to the features of its design whereby it is provided as a complete self-contained unit, the type *D* equipment is well adapted to these requirements.

With the type *D* system, it has been found practicable to eliminate the daily adjustments necessary with carrier systems operating over greater distances. The few adjustments which are required are made by means of soldered connections and are of a semi-permanent nature. These arrangements simplify the maintenance and are an important factor in making the use of the type *D* system economical, particularly in cases where the equipment is located in small outlying offices.

The office equipment for a wire circuit of a length corresponding to that of the circuit provided by a type *D* carrier system is comparatively simple and is of such a nature that the tests required to insure proper installation consist merely in checking the wiring and seeing that the various relays are adjusted properly. It has been found practicable, by assembling the complete equipment for the carrier system on a rack and testing it as an operating unit at the factory, to reduce the amount of testing at the time of installation to an item comparable with that required with the simpler equipment used with the corresponding wire circuit. This results in an appreciable saving as it avoids the necessity of shipping expensive testing equipment to the job and employing installers trained in its use. This arrangement also reduces the amount of wiring to be done at the time of installation.

My purpose in bringing out these points is to emphasize how, in the design of the type *D* system, simplifications have been included which particularly adapt it to its field of application. The use of carrier equipment has been extended so that it now proves economical on shorter circuits than heretofore, and in addition is well adapted to use in the small offices.

R. E. Kistler: It may be of interest to note the application of type *D* systems on the Pacific Coast. By the end of this year we will have 37 type *D* systems in operation in Washington, Oregon, and California, giving a total of 3173 channel-miles which you will note is about 15 per cent of the total for the Bell System. The systems are being used on circuits ranging from 35 to 150 mi. in length with an average of 85 mi. Next year we are adding 23 systems with a total of 1500 channel-miles. One important advantage in the use of this type of system in addition to the economy of installation and simplicity of maintenance is that by maintaining a few such systems in stock we can provide emergency circuits where time does not permit the stringing of wire.

Lightning Arrester Problems

New Light from Klydonograph Studies

BY A. L. ATHERTON*

Member, A. I. E. E.

Synopsis.—This paper outlines the present status of lightning arrester application on transmission lines and suggests future investigations to determine the most effective design and method of application. Information from klydonograph tests is presented to show that lightning arresters are needed on both high-voltage and low-voltage lines. It is suggested that present practise in both design and application has limitations which may be overcome with the result of better protection which will be economically justified.

MUCH valuable information has been gathered in the last few years on the over-voltages which occur on transmission lines. This information has led to some radical changes in ideas of the magnitude and frequency of dangerous voltages. Simultaneously it has given a reasonable basis for determining the need for lightning arresters, their design, and their proper application.

Most of the definite information on surge values has been obtained by means of the klydonograph developed in 1923 by J. F. Peters,[1] who conceived the idea of using the Lichtenberg figures to measure surge and lightning voltages of transmission circuits in service.

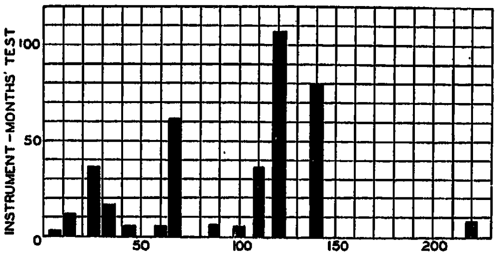

FIG. 1—DISTRIBUTION OF LIGHTNING INVESTIGATIONS BY LINE VOLTAGE

The figures had been known for years and Pedersen[2] had shown that the speed of formation is almost incredibly rapid. Peters recognized in this speed of formation one of the characteristics required in a surge-recording device. He learned, furthermore, that the size of figures varies with the voltage and that the character of the figure indicates the polarity. Subsequently he conceived and developed the klydonograph.

The device has now been in rather widespread use for four years. Much information has been gathered and this information has been made public and discussed freely.[3]

MEASUREMENTS OF LIGHTNING VOLTAGES

Klydonographs have been used in 27 investigations intended to give information as to lightning voltages. The total of instrument-months' records is 381. The distribution by voltage of line is indicated by Fig. 1, which shows that attention has been directed mainly at the higher voltages. The results are summarized in Fig. 2.

PERFORMANCE OF ARRESTERS

There have been 16 tests to record and measure the performance of lightning arresters as indicated by discharge current values, with a total of 61 instrument-months' record.

In these installations, record has been made of the voltage from line to ground at the arrester terminals and of the current flow through either one phase of the arrester or through all three phases combined. About the only fact that stands out definitely is that, based on double line voltage, or 3.5 "times normal" as the lowest surge value requiring operation of the arrester, the operation is what would be expected.

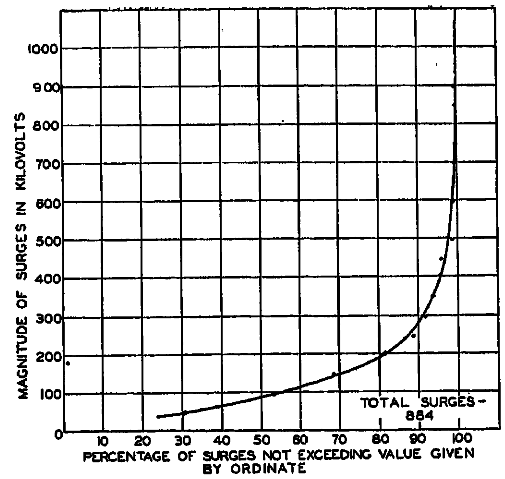

FIG. 2—SUMMARY OF LIGHTNING VOLTAGE RECORDS

MEASUREMENT OF SWITCHING SURGES

In the tests to determine lightning voltages, records have been secured as to switching surges. The results

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[1] "The Klydonograph," *Electrical World*, April 19, 1924.

[2] "The Electric Spark," P. O. Pedersen, *Ann. der Physik*, Vol. 71 (1923) pp. 317-376.

[3] *Klydonograph Surge Investigations*, J. H. Cox, P. H. McAuley, L. G. Huggins, A. I. E. E. TRANS., Vol. XLVI, pp. 315-329.

Presented at Pacific Coast Convention of the A. I. E. E., Spokane, Wash., Aug. 28-31, 1928.

show that no voltages are extremely high, very few are high enough to be dangerous at all, and that these are of such short duration as to make them of no serious importance.

DANGEROUS OVER-VOLTAGES OCCUR INFREQUENTLY

Perhaps the most outstanding of the changes in ideas indicated by these results is that dangerous voltages occur only infrequently. Before these data were available, the general idea was that there might be several hundred dangerous voltages in a season at any point on the system, and that a lightning arrester, to be effective, should operate as many times. This idea was doubtless mostly the outgrowth of observation of those early forms of arresters which were adjusted after installation so that they would spark over as often as the attendant thought proper. A little consideration of probabilities, however, will show this conception to be wrong, and that the klydonograph findings referred to above were inevitable. Fig. 3 illustrates this. Direct strokes are known to be rare and the only possible source of frequent disturbances would be induced charges. The circle of influence of a cloud has been shown by Norinder[4] and Peek[5] to be of hardly more than one-fourth mile radius. If we assume a generous average of 20 discharges in the clouds during a storm under the radius of perhaps 100 sq. mi. within the observation of the Bureau Station, the probability of any discharge taking place in a location to influence any one circuit to a dangerous extent is possibly one in three. This will be reduced further by the variation in induced voltage even for cloud discharges directly overhead, and for any one point on the line by the decrease in voltage due to resistance and corona losses, the effects of lightning arresters and line flashover, etc., as the wave travels. Bureau records show, for the Middle Atlantic States for example, an average of not more than 50 thunderstorm days per year. Then the number of dangerous voltages per year at any point should not be expected to average more than 5 or 10.

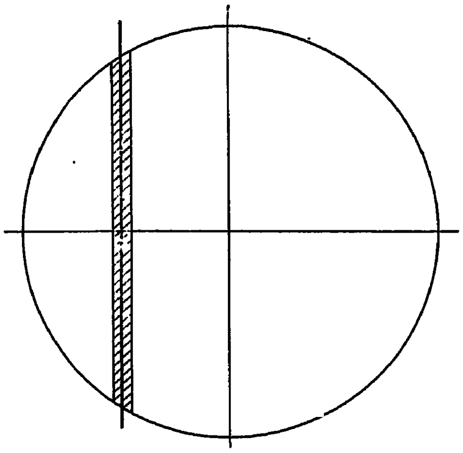

FIG. 3—SKETCH ILLUSTRATING PROBABILITY OF DANGEROUS CIRCUIT VOLTAGES DUE TO LIGHTNING

The outer circle represents the area under observation by the Weather Bureau Station and the shaded band represents an area ¼ mi. each side of the line over which the cloud discharge must take place to give rise to a dangerous voltage.

LIMITATION IMPOSED BY LINE INSULATION

A second point of significance is the almost controlling part played by line insulation in determining the results secured, and this seems likely to have the greatest influence on lightning arrester practise. Again, considering 3.5 times normal or double line-voltage value as the minimum surge requiring arrester operation, two-thirds of all the dangerous voltages caused line flashover. Ninety per cent of the voltages above seven times normal (four times line-to-line value) caused flashover. This is shown by Table I, which makes a comparison between (a) lightning surges requiring arrester operation which caused flashover and (b) those which did not cause flashover, based on average number of surges per station per year.

TABLE I
TIMES NORMAL

	3.5 to 4.9	5 to 6.9	7 to 9.9	Over 10
Lightning surges which caused flashover	1.46	0.75	1.18	0.51
Lightning surges which did not cause flashover	1.11	0.64	0.2	0.0
Per cent which did not cause flashover	43.3	45.6	14.4	0

Several thoughts are suggested by these figures. If it is granted that the voltage transmitted along the circuit after a flashover is so brief and of such small energy content as to be reduced to a safe value by transmission over a short distance and by the various electrostatic capacities within the station, then the protection afforded by lightning arresters is limited to one-half of those surges within the range of 3.5 and 6.9 times normal and one-tenth of the higher surges. Any tendency toward increasing line insulation to reduce flashover naturally increases the dependence on and need for lightning arresters.

Moreover, in concentrating them at the stations, we may not be using our arresters to the best advantage. This practise certainly limits the real benefits to approximately one-third of all the possible cases of need; and to make matters still worse, it concentrates this remaining sphere of benefit in the least necessary cases,—those which exceed line voltage by the smallest amount.

Present practise is based on the thought that a lightning arrester can do no good to any apparatus more than a few hundred feet away, and that any project to protect the line or to reduce line-insulator flashover by protective devices is hopeless. This is not necessarily true. Records over a relatively long period of time have shown in one case at least that on a long line, flashover is noticeably reduced for a distance of approximately two miles on each side of the lightning arresters. To determine the benefit empirically one or two installations have been made of arresters a mile or so apart along a line. To be sure, if such a scheme is to be at all practical, the arresters must be radically different from those we now know; at least for high-voltage service. But arresters for such use may be of relatively small capacity and can be designed to absorb and dissipate the energy of the surge so that transmission along the line is practically prevented and protection is automatically rendered to the stations.

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[4] "Electric Thunderstorm Field Researches," Dr. H. Norinder, *Electrical World*, February 2, 1924.

[5] *Lightning, A Study of Lightning Rods and Cages, with Special Reference to the Protection of Oil Tanks*, F. W. Peek, Jr., A. I. E. E. TRANS., Vol. XLV, 1926, pp. 1131-1144.

Thus it might develop that by directing our protective efforts to the line rather than to the stations, we could add to the present benefits some reduction in line-insulator flashover with little or no increase in over-all cost.

The demonstrated limitation by line insulation suggests that the station and line insulation must be coordinated to insure so far as possible that troubles occur where the damage will be least.

SWITCHING SURGES

The fact that the switching tests have shown that dangerous voltages are not to be expected from switching operations makes a rather radical change in our conception of the function of lightning arresters. It had previously been felt that lightning arresters are required for protection against both lightning voltages and those voltages arising from switching. Arresters have been recommended and used in some cases for the protection against such voltages when actual lightning voltages are not anticipated or are so infrequent as to fail to justify the installation of any protective equipment.

All arresters have been made with special provision for easy paths between lines to take care of such voltages. This use of four elements connected in "multiplex", or the similar use of an interconnection between phases at the neutral point of the arresters, introduces some disadvantages of reduced factor of safety against abnormal conditions, and is now known to be unjustified, since the compensating advantage of shorter paths between lines is not required. Since this information has been secured, general practise in lightning-arrester design has changed and three independent elements connected from line to ground are now used. Since at least 90 per cent of all arrester failures are known to be due to some overvoltage condition, and since this change increases the factor of safety against overvoltages, it is to be expected that this is a very tangible benefit of the tests.

INDICATIONS AS TO THE NEED FOR ARRESTERS

With first thought, the facts above set forth might seem to indicate that the need for protection has been over-stressed and that the use of arresters might be reduced or discontinued with safety. This, however, is not a safe conclusion as there are several cases on record in which the addition of lightning arresters has made reductions ranging from 80 per cent to 95 per cent in lightning failures of apparatus for entire systems. These are all at relatively low voltages (below 33 kv.), since the number of installations at high voltage on any one system is too small to yield a dependable average.

If it may be assumed that these cases establish the justification of arresters at the lower voltages, the klydonograph results add something to the conception as to the need for arresters at the higher voltages. First, it is established that dangerously high voltages do occur even on the high-voltage lines. Second, the fact that line insulation sets the upper limit of surge voltage reduces the low-voltage and high-voltage problems to close similarity for the most severe case. Third, so far as the data indicate, dangerous voltages occur as often on high-voltage as on low-voltage lines.

Because of the lack of klydonograph data at the lower voltages, no final conclusion may justly be drawn, but the indications thus far are that arresters are needed as much at high voltages as at low voltages.

ARRESTERS OPERATE AS PER LABORATORY RESULTS

The tests on lightning-arrester operation have demonstrated one point which previously, in one sense, has been inferred only. In the laboratory it is not possible to make complete tests on high-voltage arresters at high current owing to limitations in the amount of energy readily available and complications introduced into the measuring circuit by the large mechanical extent of the required testing equipment. Tests have been made to demonstrate that within the range which can be measured accurately, the characteristics of the sectionalized type of lightning arrester are directly proportional in voltage to the number of sections in series. This is as would be expected and the industry has continued making and using very high-voltage arresters beyond the range which has been definitely tested, on the basis that this relation holds throughout. Our assurance of this assumption is increased by the facts that the arresters have operated whenever the voltage recorded was high enough to warrant an operation and that the current values have corresponded closely with what would be expected from the voltages and the characteristics of the line.

THE PRESENT PROBLEMS

If these tentative conclusions are correct, then, although we may justify lightning arresters as now made and used, present practise limits their possible usefulness to a small fraction of the cases of real need. There is grave doubt as to whether the field of usefulness can practicably be extended to cover all the need, but this doubt is far from being a certainty. There can be no justification for failing to attack the problem even though the chances of success may seem slight, since the possible gain is so great and since no alternative has proved to be effective.

Two possible approaches suggest themselves: (1)

extension of empirical trials in service, and (2) determination of the basic data necessary to evaluate the possibilities. Both, it seems, should be tried.

The extension of the trials of arresters at intervals along the line has in its favor that it will begin to secure some results immediately and that it will stimulate the design and development effort necessary to make the scheme practicable. Against this plan is the fact that there is some expense involved and that it is far from certain that it leads to the final solution.

The approach by study of conditions deserves favor in that it will ultimately point to the correct solution. Against this are the facts that it will be very expensive and that it will require some years to make the tests, after which schemes for connection must be developed.

As valuable as the klydonograph has been, it appears that it is not going to give us all we need to solve the lightning problem. Voltage-time relations for lightning voltages must be determined and it may be necessary to eliminate the flashover limitation by over-insulation of some test circuit before the final answer is secured.

The cathode ray oscillograph opens the way to begin this phase of the problem; in fact, the work is already under way on a small scale. But very much broader tests are required. Data should be secured simultaneously in many locations distributed over that part of the country where transmission is required and where lightning troubles are likely. The efforts should be coordinated and the results gathered together for recording, analysis, and dissemination. This work cannot be left to one unit of the industry or it will not be done. It is a problem for the whole industry and requires the coordinated effort of operators and manufacturers alike to solve it.

Discussion

R. W. Sorensen: This paper again calls to mind the need for a plan which some of us for a long time have been trying to present to industrial engineers and executives interested in lightning protection, namely, the idea that the lightning problem is so big as to present possibility of solution only when undertaken as a group problem by a considerable number of investigators who together can command large resources for covering the expense, and a large number of ideas for attacking the problem.

I am quite in accord with Mr. Atherton's statement that switching disturbances can for the most part be neglected. In this connection, however, may I present a few observations made in experimenting with switches during the last few years. They are as follows: The quicker the circuit is interrupted the less the resulting disturbance; in other words, the interruption of a circuit within the first half cycle after the switch contacts are open does not produce a very high-voltage surge, as is the case if the arc between contacts is maintained for a period of several cycles.

Another source of high-voltage disturbance, arcing grounds, has been thoroughly studied, and solutions for the difficulty are now very well known. Thus we have left the real lightning problem for our chief attention in transmission and distribution lines.

There is also another phase of lightning protection to be considered, namely, protection against fire in oil reservoirs, arsenals, and structures of various kinds. In studying means for such protection we have found that it seems very difficult to predict exactly how lightning will strike because there are so many variables involved as to make accounting for all of them almost impossible. In other words, the amount of protection which can be provided by lightning rods must in final analysis be a matter of probability obtained from statistical data. We can, however, with the information now at hand, apply protection which will care for a large amount of the lightning hazard to which oil reservoirs or other structures may be subject. Having accomplished this result there is, of course, a natural tendency for industries to lose interest in the determination of the character of lightning phenomena. From a scientific point of view, however, it is obvious that best results cannot be obtained until we know more completely the true nature of lightning, and it is on this basis that I again wish to urge a comprehensive program, undertaken in part by small groups, with all groups cooperating toward the solution of the problem in the large.

C. E. Carey: I should like to ask Mr. Atherton two questions: 1, from his studies what fundamental principle has he evolved for lightning protection; 2, what records, if any, has he secured to date of transient voltages due to lightning?

F. O. McMillan: Mr. Atherton has called attention to the fact that lightning research is now in progress by several independent organizations without a coordinated cooperative program. This condition results in a duplication of effort and unnecessary expenditure of research funds, and does not produce anything like the results that could reasonably be expected from a well organized and directed joint program. A plan such as Mr. Atherton proposes should be subscribed to and supported by all of those interested in the problem of lightning protection.

As electrical engineers we may be somewhat prone to think that only the electrical industry is concerned in the lightning-protection problem, but such is far from being the fact. The protection of oil-storage reservoirs is of vital importance to the petroleum industry. Aviation interests are in need of more information about thunder storm and lightning phenomena. The United States Forest Service and various state and private timber interests have many lightning problems, three of which are very important. First, the protection of forest look-out houses on high mountains having bad lightning exposures; second, the protection of telephone lines to maintain reliable and safe communication; and third, the very serious problem of preventing or reducing the damage from lightning-caused forest fires.

This year the Oregon State Engineering Experiment Station is conducting an investigation of the protection of look-out houses and forest telephone lines from lightning. This research work is being done in cooperation with the United States Forest Service, the Oregon State Board of Forestry, and the Oregon State Forest Fire association. The importance of lightning protection for look-out houses and telephone lines in exposed locations is emphasized by the fact that several lookouts have been killed or injured by lightning while on duty.

Bradley Cozzens: Dr. Magnussen, in his address to the Spokane convention, stated that the rate of formation of Lichtenberg figures was from 7 to 10 cm. per microsecond.

In a recent article by C. L. Fortescue (*Journal of Electricity*, June 4, 1928, p. 293) it is stated that the rate of formation of an arc along an insulator string is of the order of 12 ft. per microsecond (366 cm. per microsecond). This gives the rate of flashover of an insulator string as from 36.6 to 52.3 times the rate of formation of klydonograph figures.

The length of insulator strings on transmission lines should limit the voltage that may be impressed upon the lines, for any specific rate of increase in voltage, to a very definite value. This maximum value should be approximately proportional to the length of the strings involved. Various types of shields and horns are here disregarded. It is well known, and Mr. Atherton has stated, that the voltage as indicated by klydonograph records obtained on low-voltage lines, and those as obtained on higher voltage lines with longer insulator strings, do not agree with the possible limit of voltage as imposed by the insulator string impulse arc-over voltage.

Where the insulator string is less than 40 in. long there may be an error in the klydonograph figures as a result of the difference in the speed of formation of the figure and the speed of string arc-over. This error will increase with a decrease in insulator-string length. This fact may be the explanation for the disagreement between the theoretical and indicated maximum induced voltage values.

A. L. Atherton: The question of local hazards was raised by Professor Sorensen. Each of these schemes has been shown by experience to lack something. A rather careful review of the possibilities indicates at the present time (and again I must admit that it is an indication and not a proof) that the proper way to design protective equipment is to make the voltage on the lightning protective device as high as is consistent with safety at the point where the arrester is connected. The practical application of this thought results in what is almost a reversal of ideas in lightning-arrester design.

Under the old idea our aim would be to produce an arrester which has a constant volt-ampere characteristic which lies only slightly above line voltage. Our aim under the present idea is to produce an arrester which has a similar characteristic but one which lies well above line voltage, probably between 2 and 2½ times line voltage. The idea is that within this range the higher the voltage the greater will be the amount of energy taken out of the lines, and the less likely will be the passing along or reflecting back of the transient on the system to cause damage at a second point. This change in attitude of mind toward the lightning-arrester design problem is not wholly formulated, but has a great deal of support.

Mr. Carey also asked as to the records secured in our Tennessee investigations. One good record of lightning voltage has been secured with the oscillograph. This was supported by parallel klydonograph records, verifying the crest value of voltage. The information secured is of interest and significance in that a first conception of the voltage rise and duration is secured. For instance, the voltage rose at a relatively uniform rate during a few microseconds to a crest value of 650 kv., and fell along a somewhat irregular line to zero, the total duration being approximately 50 microseconds.

On the other hand, the point of main significance is a complete demonstration that there are now available the necessary instruments to secure results of this sort with reliability. In other words, we have demonstrated that we are now in a position to determine the entire course of the transient voltage from beginning to end, registering every variation by the mere application of instruments already developed.

Another point of major importance is that only one opportunity for a record has been available during the duration of the test thus far approximately two months. This indicates the need for the use of a rather large number of instruments, probably well distributed over the country, if we are to get the necessary information as to the extreme and average or ordinary values of rate of voltage rise, maximum voltage, and the duration in a reasonable number of years.

These findings support the suggestion that coordinated effort is necessary.

Professor McMillan mentioned the study which is being made in connection with the protection of forests against lightning damage. He referred to the protection of oil tanks. It is interesting to note that the United States Navy Department and the Army Department are interested in the problem of thunder-storms from the standpoint of aviation. Several very serious accidents have occurred due to lightning storms. Some thought that some of the airplane failures have been due to lightning.

The fact that this kind of study is applicable to several industries, the fact that it is widespread, and the unfortunate fact that there is very little definite provision for coordination between these different studies, further support the necessity for setting up some kind of national guiding organization.

Mr. Cozzens has brought up an interesting point. We must be careful, in thinking of the data in regard to speed of either flashover or formation of the Lichtenberg figure, not to overlook the fact that the values are not precise and that they are not on the same basis. The speed of formation of the Lichtenberg figure is exponential. That is, the formation is very rapid at the start and gradually becomes less, so that even though it may take 0.1 microsecond to form a figure 1 cm. in radius as stated, a very large part of the same figure forms in a small fraction of 0.1 microsecond.

As to the basis of time, the Lichtenberg figure begins forming with the beginning of the voltage rise and in general can substantially keep pace with any surge which does not rise to its crest in a very small fraction of a microsecond. On the other hand, the flashover of the insulator does not begin until a considerable overvoltage value is reached, this value being of the order of the crest value of 60-cycle dry flashover. The time for insulator flashover begins at this point, when the Lichtenberg figure is quite well formed.

There is evidence that the accuracy of the klydonograph decreases somewhat when the wave front is made extremely steep, or in other words, when the voltage application is extremely short, but this inaccuracy is far from being as great as might be indicated by the figures Mr. Cozzens cited.

It is our laboratory experience that measurements made in parallel by the klydonograph and by sphere gaps usually result in not lower but rather higher values by the klydonograph.

High-Voltage Phenomena in Thunderstorms

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Associate, A. I. E. E.

Synopsis.—Lightning phenomena are analyzed in the light of laboratory experience with high-voltage phenomena in the atmosphere. Special emphasis is placed on the effect of space charges in producing high local stresses when mobilized through channels of high conductivity caused by high temperatures. A detailed analysis is included of the steps through which air at atmospheric pressure passes when, due to applied electric stresses, its electric properties change from those of a non-conductor to those of a highly conducting body,—perhaps many times as conducting as a metallic conductor at ordinary temperature,—and then again resumes its original non-conducting properties.

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THE electrical quantities involved in thunderstorms are of an order of magnitude different from those encountered in ordinary engineering experience. In the laboratory, sparks 20 ft. in length have been obtained with an applied potential of 2,000,000 volts, 60 cycles. Compared with a lightning flash several miles in length these results seem puny indeed. Yet the results obtained in the laboratory enable us to analyze the phenomena occurring in nature, and thus obtain a clearer mental picture of the mechanism involved in the formation of lightning flashes. Such a procedure should prove of great value in obtaining and interpreting evidence relative to lightning to be used in determining the most effective means of protection.

It is very desirable to lay particular stress upon the chief differences between electrical phenomena in thunderstorms and in engineering practise. We are ordinarily concerned with complete metallic circuits handling large quantities of electricity at constant and relatively low voltages for long intervals of time. On the other hand, in a thunderstorm the quantities of electricity present are small, in the form of isolated electric charges located on water drops forming a volume distribution of electricity. The masses of the water drops are so large compared to their charge that, for the duration of a lightning stroke, the distribution of electric charges remains fixed. The charged water particles are acted upon by the electric field and their slow motions give rise to displacement currents. The actual velocities attained by the charged particles are sufficiently low to enable the wind to do work upon them against the electric field and thus raise the potential to breakdown of the air, when a lightning flash takes place. The voltages present in thunderstorms may be extremely high, of the order of 100,000,000 volts, and are subject to wide and sudden variations. While the quantities of electricity in lightning flashes are small,—of the order of 20 coulombs—yet as the time during which they are mobilized is short, the current in a flash might rise to 10,000 amperes. The total energy released in a lightning flash is not large, but the rate of expenditure of this energy may be tremendous.

In order to understand the mechanism of formation of a lightning flash it is necessary to have in mind the behavior of air at atmospheric pressure when overstressed. For a simple configuration of the electrodes mathematical physicists give us expressions for the current in terms of the physical quantities involved. A spark is said to pass when the current, as determined by the expression, becomes infinite. When the electric field is at all complex, the mathematical solution becomes too involved. Needless to say, it would be quite out of the question to determine mathematically the particular path to be taken by a lightning flash even though the initial configuration of the field were known. This particular path depends upon a combination of numerous small causes, or guiding circumstances, so that it should be possible to show the general tendencies of the discharge by the use of statistical methods.

The conductivity of the atmosphere is due to the presence of ions which, when acted upon by an electric field, give rise to a displacement current. If it were not for these charged particles, air would be a perfect insulator. Ions are always present in the atmosphere, as they are formed spontaneously due to the action of traces of radio active matter, cosmic rays, etc. However, the conductivity which these sources of ions lend to the atmosphere is so small that it has no engineering significance. When the saturation current is not reached, that is, when the ions are not removed by the field as fast as they are formed, then the current through the air is proportional to the voltage gradient and to the cross-section of the path. In symbols, the relation is

$$I \alpha G . A \qquad (1)$$

where I is the current, G the voltage gradient, and A the cross-section of the path considered.

Relation (1) represents the behavior of air under low voltage stresses.

When the voltage is gradually raised, the saturation current is soon reached. The voltage can then be raised considerably without change of current. However, as soon as the voltage gradient at some point in the field reaches 76 kv. per inch, the current suddenly increases. This is due to the cumulative effect of collision ionization. Ions present in the field are then so accelerated between collisions as to possess sufficient kinetic energy to produce new ions when they collide with neutral

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atoms. The rate of formation of ions is thus enormously accelerated. The clouds of ions thus formed are referred to as space charges and greatly disturb the original electric field. The action of space charges upon the electric field is always such that it prevents the gradient from rising above the critical value of 76 kv. per inch where the stress is most intense. Outside the region of breakdown the gradient is increased above the value it would have for the same applied voltage if the space charge were not present. This is illustrated in Fig. 1, *a* and *b*. The body *A* is at a positive potential and *B* at a negative potential, the configuration being such that the electric field diverges from *A*. If the potential between *A* and *B* is raised, the gradient in the neighborhood of *A* soon reaches the critical value for air. Collision ionization then enormously increases the supply of ions in that region. The negative ions travel towards *A* and become discharged. The positive ions travel toward *B* and form a space charge. At 1*b* the applied potential is much greater than at 1*a*, yet the gradient in the neighborhood of *A* has not been increased. However, the gradient between the space charge and *B* is greatly increased, as shown by the additional lines of force originating on the space charge and terminating on negative charges at *B*.

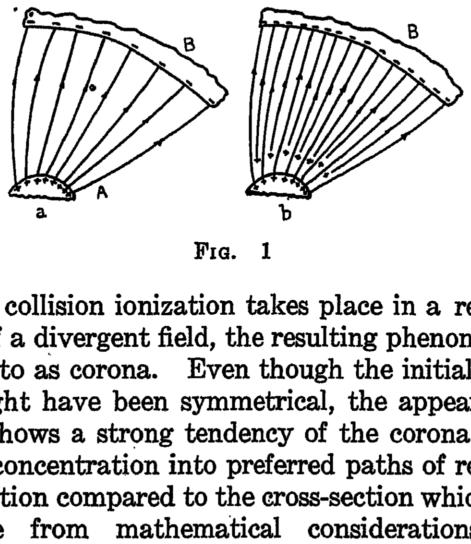

Fig. 1

When collision ionization takes place in a restricted region of a divergent field, the resulting phenomena are referred to as corona. Even though the initial electric field might have been symmetrical, the appearance of corona shows a strong tendency of the corona current toward concentration into preferred paths of restricted cross-section compared to the cross-section which seems available from mathematical considerations. This tendency results in the formation of corona streamers. It may be represented in symbols by the relation

$$g \,\alpha\, A \,.\, F\,(i) \qquad (2)$$

or the conductance, *g*, varies as the cross-section of the path and some function of the current density, *i*. The function *F* (*i*) is such that the increase in conductance resulting from an increase in current density more than offsets the decrease due to the reduction in cross-section.

Because in relation (2) the conductance of the path increases with a reduction in cross-section, the behavior of air under these conditions may be referred to as unstable, or abnormal, while the behavior of air when relation (1) holds may be called normal, as it is by far the most common in our experience.

The voltage which just causes corona to appear in the most stressed region of a divergent electric field is called the critical voltage. When this critical voltage is exceeded space charges are planted due to the action of the field upon the ions formed by collision in the corona region. The planting of these space charges can be referred to as being due to the flow of corona current through the overstressed air. The amount of corona current flowing depends upon the excess voltage applied above the critical voltage. It is evident that the corona current must be thus limited, because the space charge resulting from an excess of current would decrease the voltage gradient in the most stressed region of the field to such an extent that collision ionization would stop, thus effectively preventing a further increase in space charge.

The abnormal behavior of air when relation (2) holds can be illustrated in words as follows. Due to an increase in current density:

a. The SAME current is transmitted at a LOWER voltage gradient when the cross-section of the path is reduced;

b. For the SAME voltage gradient MORE current is transmitted through the air when the cross-section of the path is decreased; or

c. MORE current is transmitted at a LOWER voltage gradient when the cross-section of the path is reduced.

The formation of corona streamers is the first stage in the building up of preferred discharge paths of restricted cross-section. Although the exact mechanism of formation of corona streamers is not known, it is practically certain that it cannot be due to an increase in temperature causing a reduction in air density with a corresponding decrease in the critical gradient required for cumulative collision ionization. The various manifestations of corona, such as light, sound, and chemical changes, show that considerable ionic activity is present in corona streamers. Physicists give us plausible reasons why such intense ionic activity in corona streamers should have a tendency to lower the critical gradient of cumulative collision ionization. Some results obtained by them with the discharge tube suggested that the bluish light observed was not due directly to the recombination of ions. At the low pressures used, the velocity of the ions due to the electric field would be such that the Doppler effect should be observed. As this is not the case it has been concluded that the sources of light were neutral atoms not affected by the electric field, and consequently at rest. An explanation which has been proposed is that when ions of opposite sign recombine to form neutral atoms, *i. e.*, when a positive nucleus recaptures a lost electron, the quantum of energy radiated is in the form of very short wavelengths outside the visible spectrum. These rays are supposed to have a very limited range. They have the power to excite neutral atoms, that is, they furnish sufficient energy to a neutral atom to lift one of its electrons from an inner stable orbit to a less stable outer orbit, where the electron possesses potential energy with respect to the nucleus. The electron upon falling back to a more stable orbit radiates this energy at a longer wave length which falls in the visible spectrum. It is this light emanating from neutral atoms which is observed.

With the above in mind, we must consider that the intense ionic activity in a corona streamer is due to the active recombination of ions constantly taking place. Due to such active recombination a considerable number of neutral atoms in the streamer is excited, that is, the electron has already been furnished part of the work required for complete ionization. For these excited atoms a collision of lesser magnitude, corresponding to a lower voltage gradient, will suffice to complete the work of ionization. Such a mechanism explains why the space charge can be mobilized through corona streamers at voltage gradients slightly lower than would be required in the surrounding space.

As the current density in a streamer further increases, temperature begins to play a more important part. In the final stage, a high degree of conductivity, perhaps greater than that of metallic conductors of the same cross-section, is imparted to the filamentary channels due to the very high temperature attained as the result of the large amount of energy released per unit volume in the conducting path. It is probable that when the temperature in the filament is sufficiently high, the violent thermal agitation of the gas suffices to keep up a supply of ions great enough to account for the high conductivity attained. This final stage in the condensation of the discharge into narrow filamentary channels lends itself particularly well to analysis and will be discussed here, but it must be remembered that the change from the initial corona streamer is gradual and not in distinct steps.

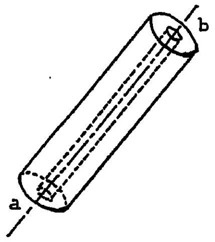

Fig. 2

Let us assume that a discharge is being transmitted from a to b, Fig. 2, along a cylindrical path. Some heat will be generated by the passage of the discharge. At low temperatures the heat will be dissipated mostly by conduction or convection across the cylindrical boundary surface. We can reasonably assume that the conductance of the path varies in some manner with the temperature, T. This will be the case when the thermal agitation of the gas becomes so high that a certain proportion of the collisions will result in ionization. Theoretically, for any temperature above absolute zero, some velocities will be sufficiently high to cause ionization, but the probability of such velocities at low temperatures is vanishingly small. However, this probability increases rapidly with the temperature. The ions when free are acted upon by the electric field and subjected to a drift which is superimposed upon the random thermal agitation and is equivalent to a current. Thus the path has some of the properties of metallic conduction. The current will depend upon the proportion of free ions, and this in turn will depend upon the temperature. We can therefore write

$$g \alpha A \, . \, F\,(i, T) \qquad (2a)$$

or the conductance varies as the cross-section of the path and some function of the current density and temperature.

This relation is essentially unstable, because the temperature reached is caused by the energy loss per unit volume, and therefore depends on the current density, and the current density for a given voltage gradient depends on the conductivity which increases in some fashion with the temperature.

Coming back to the cylindrical path a–b, Fig. 2, the heat generated by the passage of the discharge must at first be dissipated mainly by conduction or convection through the cylindrical boundary. Therefore, the temperature reached in the interior will be higher than the average, so that the degree of ionization will also be higher. As the conductivity increases with the ionization, the current density will not remain uniform but will be higher where the temperature is higher. This means that in a restricted region of the path along its axis the rate of dissipation of energy will be increased, causing a further increase of temperature. This process continues until some limiting action takes place, so that finally the discharge will be concentrated in a narrow thread-like filament and will require a smaller voltage gradient than initially.

The limiting action referred to is not far to seek. When the temperature is very high, radiation has a greater influence upon cooling the filament than conduction. The radiation of a black body varies as the fourth power of the absolute temperature, and such a relation is more than ample to limit the path to a finite cross-section by limiting the temperature which the filament might attain.

Work done by physicists on exploded wires gives some idea of the characteristics of gaseous thermal dissociation filaments. The temperatures thus reached are the highest attainable. The ionization is so intense that the gaseous column is opaque to light because the free electrons impart to it some of the optical properties of metals, even though on account of the high temperatures reached the density of the gaseous column is very low.

In a thundercloud, positive and negative charges are distributed throughout great volumes of cloud in the form of large ions having low mobilities. It is convenient to represent the stress to which the intervening air is subjected by drawing lines from any suitable unit of positive charge to a similar unit of negative charge, as shown in Fig. 3. These lines are always at right angles to the equipotential surfaces, the traces of which are also shown in Fig. 3. The number of lines crossing a unit surface normal to them is a measure of the stress

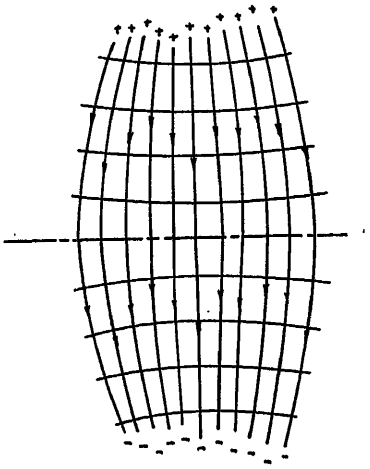

Fig. 3

at the point considered. Hence, the stress, or voltage gradient, is greatest where the lines of force are closest together. In Fig. 3 the lines are drawn from a positively charged portion of cloud to a negatively charged portion,—or the neutral plane might be considered to represent the ground surface, in which case the negative charge is an electrical image of the positive charge—a great help in computing the field between a charged body and the ground.

If in Fig. 3 we consider the neutral plane to be the ground surface, it is seen that the stress is smallest at the ground because the lines of force are farthest apart there. This will always be the case, as the lines of force must either originate or end on the charges in the cloud depending upon the polarity—a pure convention—but will then spread apart in such a manner that the permittance of the path between cloud and earth is maximum. Due to irregularities at the ground surface there will no doubt be high local stresses, but even if breakdown takes place, this as a rule will result only in the formation of a local space charge which will be sufficient to relieve the stress, because the volume of overstressed air is small. Breakdown will generally take place in the cloud due to the wind shifting the charges in such a manner that a large volume of air becomes overstressed. This is necessary in order that sufficient energy be available for the formation of filaments of high conductivity. These conducting paths then transmit the high stresses to their end points and lengthen by successive breakdown of the air.

The manner in which a filament of high conductivity transmits the stress to its end points will now be illustrated. Fig. 4a shows the lines of force in a parallel field, the voltage gradient being considerably below the critical value for air. Let the dotted line represent a channel of high conductivity caused by thermal dissociation. This channel contains both positive and negative ions in equal numbers so that their total effect upon the external field is zero. The ions continually form and recombine, the percentage of atoms ionized at a given temperature of the channel remaining constant. While the ions are free they are acted upon by the electric field, so that a small unidirectional shift is superposed upon their random thermal agitation, the positive ions shifting towards one end of the filament and the negative ions shifting towards the other end. This takes place along the whole length of the channel, and although each ion may shift only slightly, if their number is large the total effect might represent a very large current. Due to this shifting caused by the electric field, ions of one sign will accumulate at one end of the filament and ions of the opposite sign at the other end. Such an excess of ions of one sign at the ends of the filament alters the original field in a manner shown at 4b. It is seen that the gradient at each end of the filament has been considerably increased, while the gradient along the filament, which causes the shifting action, has been decreased.

If the energy initially stored in the dielectric is too small, the shifting action in the filament will cease as soon as the voltage gradient along the filament falls to a sufficiently low value. This will happen before the critical gradient for air has been reached at the end points. The conductivity of the filament is due to the high temperature caused by the passage of the current in a very restricted channel, and as soon as the current decreases the filament will cool and its resistance will increase. This will decrease the current still further, resulting in additional cooling and increase in resistance. This action will continue at an accelerated rate until all traces of the path have disappeared, just as if a switch had suddenly been opened.

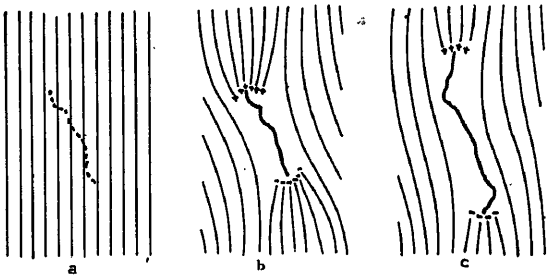

Fig. 4

On the other hand, if the energy stored in the dielectric is sufficiently high, then the critical gradient for air will be reached at the end points before the gradient along the channel has fallen to the point where the resulting current fails to maintain thermal dissociation in the channel. As soon as the critical gradient is reached at the end points, collision ionization takes place and corona streamers form radiating outward from the point. As a rule, thermal dissociation will first become effective in one of these streamers. When this takes place large currents will flow along this streamer in the manner outlined above, resulting in a considerable reduction in the voltage gradient. The high gradient required to maintain the action along the other corona streamers having collapsed, the activity in them will stop. Fig. 4c illustrates the lengthened channel, showing already an accumulation of charges and increased gradients at the end points. The channel continues to grow in this manner as long as the gradients at its end points reach sufficiently high values to cause local breakdown of the air.

The conductivity reached in a channel where thermal dissociation takes place depends solely on the current density and resulting temperature, so that the gradient along the channel may fall to a value as low as a few hundred volts per foot, while the original gradient may be as high as 100,000 volts per foot. Thus, as soon as the conducting channel reaches a length of several hundred feet, the energy available to cause breakdown at its end points becomes very large. The voltage gradient accumulating at the end points is limited by the breakdown strength of air which results in lengthening the channel. The voltage used up in this manner might reach five million volts. For a strong initial field, the rate of breakdown and lengthening of the filament increases.

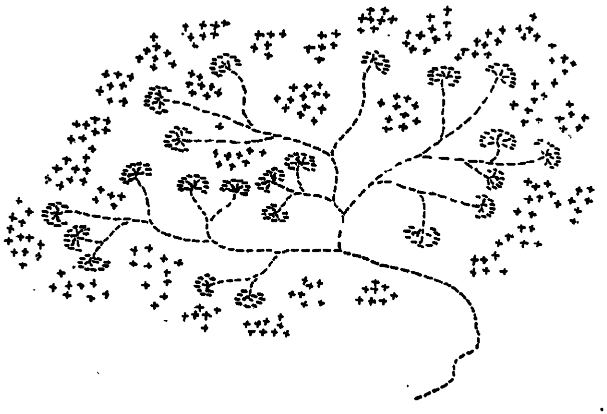

Fig. 5

The channel will continue to increase in length, branching out in the clouds wherever the necessary gradient is available, until the potential of the cloud has been so reduced that the current density in the channel can no longer be maintained, when the action stops in the manner outlined above. Fig. 5 illustrates a cloud discharged in this manner. The dotted lines show where the conducting filaments were located. It will be seen that the initial charges are still located in the cloud. Wherever the gradient was sufficiently high, ionization channels formed which planted space charges of opposite sign throughout the body of the cloud. The potential of the cloud has thus been considerably reduced. The gradient between opposite charges in the cloud is still quite high, and the charges gradually neutralize each other due to convection. However, the resultant gradient between cloud and earth has fallen to such a low value that it cannot permit the growth of, or even maintain, conducting channels.

The above analysis shows that any oscillatory discharge of the cloud is out of the question. Some authors have come to the conclusion that the current in a lightning flash rapidly alternates by assuming the cloud to be a conducting surface, forming a condenser with the earth, while the main flash formed a low resistance path between the oppositely charged plates of the condenser. When it is considered that the charges in the cloud reside on water particles of very low mobility isolated from one another, and that the final branching of the flash in the cloud must be composed of corona streamers requiring gradients of the order of 10,000 volts per inch, while collision ionization at their end points requires 76,000 volts per inch at normal air density, it becomes apparent that a very high resistance is at all times in series with the main discharge path, so that the discharge of the cloud cannot even proceed until ground potential has been reached.

In the cloud, conducting channels will branch out in various directions wherever the requisite gradient for their growth is available. Along the main flash, however, where the initial field is approximately parallel, the branching of the conducting channel requires that two corona streamers shall pass simultaneously through the same values of temperature and conductivity. Should the conductivity of one of the streamers become greater than that of the other, the voltage gradient will fall too rapidly to allow the other streamer to continue its growth and the air in it will quickly resume its original non-conducting properties.

While the probability of the branching of the main channel at any one local breakdown is small, photographs of lightning often show flashes in which such branching has occurred. Each branch then grows independently of the other. As a rule, one of the branches will connect to earth before the other and its brilliancy will greatly increase due to the great increase in current density and temperature caused by the discharge of the cloud. The electric field between cloud and earth will then fall to a value so low that it does no longer allow the other branch to continue its growth. The main flash will thus appear in the photograph to be much brighter, while the fainter branch apparently terminates in mid-air. However, there have been quite a few reliable observations of lightning in which both branches of the flash connected to earth at the same time, so that the discharge current divided itself equally between them and they attained the same brilliancy. There are even reliable reports of three such branches connecting to earth simultaneously. The above analysis shows how vanishingly small the probability of the latter event must be.

As a rule, the main branches discharging various portions of the cloud will not grow simultaneously, but instead will succeed each other in time, perhaps overlapping to some extent. At any event, the maxima of current in the various branches will not occur at the same time. When one of the main branches taps new portions of the cloud, the current in the main channel will increase, resulting in an increase in its temperature and in the amount of light it radiates. Thus, coincident with the growth of the large branches discharging the cloud, the main channel will radiate light of increased brilliancy. This is strikingly shown in photographs of lightning with a moving camera, the maxima of brilliancy appearing as parallel flashes on the photograph.

The main channel of a lightning flash forms a very effective radio antenna. The current in this channel rises rather slowly, reaching a maximum in perhaps 0.01 second. However, as the main current is the resultant of numerous local breakdowns in the cloud occurring more or less at random, it will not vary uniformly. There will be pulsations of current of large magnitude corresponding to the formation of the main branches discharging the cloud. These can be heard directly in a telephone receiver connected to an antenna. Besides these large pulsations of current, there will be smaller ones corresponding to the growth of the smaller streamers, some of very short duration giving an impulse which will affect a radio antenna by causing it to swing at its own frequency.

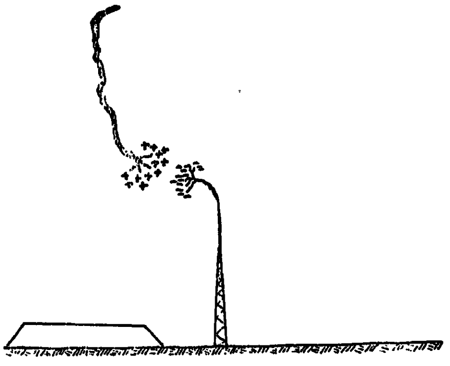

Fig. 6

It remains to indicate what bearing the above analysis may have on the possible application of a scale factor to laboratory experiments in lightning protection. Even the tallest lightning rods distort the general field of a thundercloud to such a slight extent, that they scarcely can have any influence on the instigation and guidance of a lightning flash. Whenever a lightning flash originates in the clouds and grows toward a lightning rod, during the period of growth the gradient at the rod increases, at first slowly, then more rapidly as the end of the conducting channel comes closer to the rod. When it approaches within less than 100 feet from the rod, the gradient at the rod might reach a value of the order of 300,000 volts per foot. This is illustrated in Fig. 6. The voltage gradient and volume of overstressed air at the rod then becomes sufficiently great to permit the formation of a streamer of high conductivity starting out from the rod and growing in the general direction in which the field is most intense. When this occurs, the gradient between the ends of the growing lightning flash and the streamer from the rod may reach values several times as great as the gradient in any other direction, and the two ends therefore grow towards each other until they ultimately connect. This explains why lightning hits elevated points which initially do not sufficiently distort the original field to guide the flash.

Similar considerations show why some lightning transients on transmission lines may have steep wave fronts of the order of a few microseconds. If a lightning discharge strikes very close to a transmission line, the voltage gradient at the point of nearest approach first increases slowly, reaches a maximum, and then suddenly collapses in the time required for the flash to bridge the last 100 feet or so of the gap. The latter time depends upon the driving power behind the flash, that is, the energy initially stored in the electric field of the thundercloud.

In the case of very small scale laboratory experiments, the volume of overstressed air around the grounded point is not sufficient to allow the formation of streamers of high conductivity, and the protective ratio obtained is likely to be too low. There is also the danger of having the scale of the experiment so small that the successive breakdown of air in an actual lightning flash is no longer simulated. As the cloud in laboratory experiments is replaced by a conducting surface, the manner of discharge of a thundercloud by means of streamers branching out throughout its volume, and the resulting gradual rise of the current in the main flash, pulsating to some extent, is never simulated in the laboratory.

To increase the effectiveness of a protective installation, it is desirable that the objects to be protected be given such a shape as to prevent breakdown of the air (as at sharp corners), under the intense stress just before the flash connects to ground, thus decreasing as much as possible the chance for the formation of conducting streamers. On the other hand, the protecting towers should be so located as to allow the formation of these conducting streamers at as low a stress as possible, to increase the likelihood of the flash connecting with them.

It must be kept in mind that the culmination of a lightning flash striking a particular object is the result of a particular combination of numerous small causes, or guiding circumstances, so that protection can seldom be made absolute. "Freaks" will occur when the combination of circumstances is particularly unfavorable to an exposed object, while at the same time favorable to a less exposed object, so that a streamer from the latter actually connects with the flash. The probability of such an unfavorable event can perhaps be made vanishingly small by paying close attention to the contributing factors outlined above.

In the above analysis of the behavior of air in thunderstorms no distinction has been made between positive and negative clouds, because it is believed by the author that present high-voltage laboratory experience does not warrant such a distinction. Although the volumes of overstressed air in the laboratory are rather small, yet the voltage gradients attained are as large as those occurring in thunderstorms. Space charge studies show that negative ions do not necessarily travel farther than positive ions in these intense fields. For small stresses there are striking differences between positive and negative corona. However, when photographs of arrested spark discharges are obtained, showing the initial growth of streamers under sudden stresses, no striking differences can be observed between streamers growing out from either a positive or negative body.

Reliable field observations may show that there are striking differences between flashes from positive and negative clouds. Even so, it is believed that the qualitative analysis presented above, based on considerations which perhaps are too general, will enable observers to secure data giving us a better understanding of lightning phenomena.

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Discussion

H. J. Ryan: Study of "ultimates" has established the identity of the electric spark and of the lightning stroke. It would be meticulous to particularize wherein they differ in essential qualities. Surely they have this much in common: metallic or other conducting electrodes are unessential. They are discharges through conducting air channels of intense ionization and high conductivity that develop with extreme suddenness when the voltage gradient in the corona discharge channel exceeds a certain critical value. The channels develop high temperatures and intense thermal electromagnetic radiations that are both luminous and non-luminous.

In the thunderstorm the scale of operations is such that lightning occurs with facility between the opposing charges held in clouds or between clouds and earth. In the laboratory this facility of spark-discharge without metallic electrodes is rarely encountered. The best we have found so far was suggested by members of our present laboratory personnel. Two 500-watt gas-filled, incandescent lamps were mounted axially as the discharging electrodes of a 60-cycle high-voltage source, neutral grounded, with their tipless bulbs in face opposition, about one-fifth of their diameters apart. The action to be inaugurated was materially enhanced by the connection of an air-core condenser of almost any convenient, available size, in multiple with the lamp electrodes. As the voltage was raised the gas in the lamps was ionized and the resulting space charges were moved up and bound to the insides of the opposing faces of the lamp bulbs. As the voltage was further elevated, the air in the open space between the outer walls of the lamp bulbs was overstressed. Ions resulted in abundance that were rapidly separated by the electric field and driven to their respective bulb faces on the inner walls of which there were bound charges of opposite polarity. Then the charges thus placed on the outer walls of the bulbs were reversed by spark-conduction through the open air in the succession of ensuing alternating voltage crests. They were the snappy, blue-white, enormously quick discharges that we know to be sparks in which metallic electrodes have no direct function. Fig. 1 herewith is a reproduction of a photograph of a small series of such sparks.

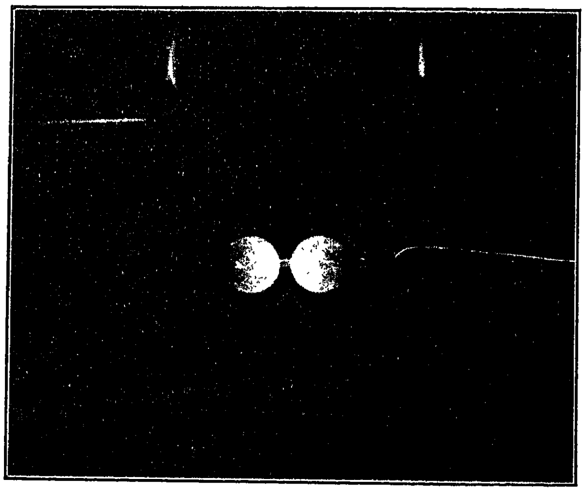

FIG. 1

When 60-cycle voltage at a value near to flashover is applied with the neutral of the source grounded, between pointed metal electrodes, 20 ft. apart, they are covered profusely with corona and at irregular intervals of a few seconds, sparks that terminate abruptly in space having a length of several feet are produced from each electrode. Each spark appears blue-white, with a snap. To the unaided eye it terminates abruptly. Through the telescope it is seen to terminate in a brush of a few straight, highly divergent, short streamers. We believe these to be substantially a laboratory form of the spark-streamer attached to the lightning rod in Fig. 6 of the Lissman paper. Our laboratory personnel obtained photographs of some of these sparks with a quartz lens from which they scaled lengths. Fig. 2 herewith is a reproduction of a pen-and-ink tracing of one of them, made in an optical projector. They have not photographed well enough for direct reproduction.

To focus one's mental picture of lightning the author has recognized and specified three distinct stages of electrical conduction in thunderstorms:

1. Convection of ions.
2. Corona, visible as glow, brush, and streamers.
3. Lightning, the nearest laboratory form of which is the spark.

In specifying the cause of the transition from the corona to the lightning stage of conduction he has used the hypothetical term "thermal dissociation." The difficulty with this term is due to the fact that many will assume that the intense ionization constituting the advanced degree of electrical or physical dissociation that occurs in the spark or the stroke is thus specified by the author to be the result of high temperature. Now high temperature and thermal effects may differ greatly. Some physicists have shown that high temperature will not account for the intense ionizations present in the spark. Others appear to be finding that thermal radiations including their near relatives, the luminous or ultra-luminous radiations, do facilitate ionization. Thus the author selected the term *thermal dissociation* to specify the group of causes that bring about the intense ionization in the spark and in the lightning stroke.

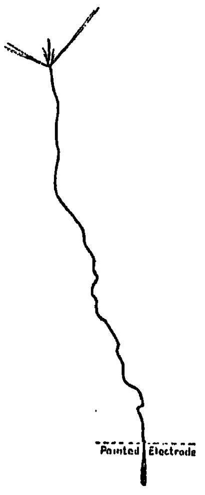

FIG. 2

The author's view that the numbers of positive and negative ions in the lightning stroke (or spark channel) at any one instant are equal, is also hypothetical. The view doubtless facilitates the approximation of the focus of the true picture for present practical purposes. Only subsequent study can determine more definitely this phase of the conditions present in the spark channel.

On the whole I am much indebted to the author for this paper because of the mental picture of lightning that it has established. It will help in our work of alert observation of the actual lightning occurring in thunderstorms and of its close relative, the spark, in the laboratory. For it is only through further, well directed observations and the analysis of the results obtained therefrom that the true nature of lightning will eventually become more abundantly known.

R. W. Sorensen: Mr. Lissman's paper again gives us opportunity to emphasize the need of research as to the character of lightning. In providing protection for oil reservoirs certain experiments have been conducted, all of them based largely on the assumption that properly erected lightning rods well grounded may be relied upon to protect a rather large area around the rod. The data led us to believe that under certain conditions we might always have protection from a rod over a distance of four times rod height. Further experiments, however, have certainly indicated that no such general law can be made. The oil companies in California have erected lightning rods or towers, the spacing of which is determined on the basis that a rod will protect a distance of about two and one-half times the rod height. Our laboratory work indicates that even this protection cannot be considered as absolute because often some condition arises which causes a lightning stroke to behave differently from that of many other strokes. In such cases rods do not protect for a distance of even two and one-half times their height.

I have observed a lightning storm in which for more than half an hour the number of strokes was in excess of 100 per minute. I do not know what portion of the strokes were between clouds and ground and what portion were from cloud to cloud. This observation confirms the fact that in many cases the accumulation of charge occurs at a very rapid rate; in fact, at a rate so great as to eliminate most certainly one proposal which has gained a great deal of attention; namely, that by the erection of a large number of small points, as for example a high fence of barbed wire, the charges might be dissipated so rapidly as to prevent lightning strokes. The observation of such a storm as this indicated that aviation will introduce lightning problems which at present are practically unknown to us.

H. E. Mendenhall: I believe some of the terms used in this paper are not in agreement with the usual practise. The author uses such terms as, "thermal ionization," and "thermal dissociation" in such a way as to confuse their true meanings.

By "thermal dissociation" I assume he refers to the process of ionization by collision which occurs at high temperatures as a result of collisions between very fast-moving ions and atoms.

By "thermal ionization" I believe he refers to the process of ionization by radiation known as the photoelectric process. If so, I feel that the expression "ionization by the photoelectric process" used in place of "thermal ionization" would be more expressive in this connection.

Bradley Cozzens: Many theories have been advanced as to the manner of formation of lightning. This very intensive paper is, for the most part, in line with the generally growing idea that lightning cloud voltages are not nearly so high as previously conceived. Lightning voltages have been estimated to be of the order of 300,000,000 volts, while very recent investigations indicate that the value may be of the order of 10,000,000 to 30,000,000 volts.

Going back to Dr. Steinmetz and his investigations with Mr. Peek, and the early studies of Dr. H. J. Ryan, on the electric strength of thin air films, it has been found that any gap up to 0.001 in. will require 0.32 kv. to rupture. To rupture gaps up to 0.07 in. requires voltage gradients up to 20 kv. per in., and for gaps from 0.07 in. up to 100 in. requires average voltage gradients across the gap of from 8 to 10 kv. per inch in order to rupture, depending upon the formation of the field. In a paper by Professor Carroll and myself (*Sphere-Gap and Points-Gap Arc-Over Voltage as Determined by Direct Measurement*, p. 1) it was found that this average value of voltage per inch necessary to break down gaps 180 in. in length between a point and plane had been reduced to 6 kv. per inch. It is not wished to convey the idea that these values will decrease indefinitely, but the general trend of all of the investigation so far conducted is for the average value of voltage per unit distance necessary for breakdown to decrease with the increase in gap length.

Mr. Lissman has pointed out the manner in which negative streamers may be formed from an electrode. In further explanation of the formation of streamers I should like to present the following theory. There is apparently a resistance, valve action between the cloud and the streamer, which we will call "entrance resistance." Any streamer that may start from a section of the cloud will have inductance and resistance, and also capacity to the cloud and to earth. The resistance of the streamer will be low compared to the inductance for it is well known that the conductivity of an arc stream is as great as 1000 times that of metal conductors.

The cloud itself has capacity, but it is impossible to conceive of a current flow back into the cloud in the same manner in which it is drained from the cloud, which would be necessary were the cloud to be included in the oscillatory circuit. However, the streamer itself, being a low-resistance conductor, may support oscillation. It has long been known that high-frequency voltage will produce much longer streamers than a similar value of voltage continuously applied. Further, as the streamer increases in length, the inductance increases, and the frequency or natural period of the streamer is decreased. With this decrease in frequency, the energy radiated electro-magnetically per unit length is also decreased.

Mr. Lissman has called attention to the fact that ionization as caused by a spark in air persists for some time after the flow of current has ceased. The flow of current into a streamer will not be continuous and as a result, at the time the current ceases there may be considerable potential built up between sections of the cloud and the old streamer channel. Since this old streamer channel is the point of greatest potential difference, the cloud will again discharge into the streamer and will cause the streamer to progress a greater distance due to the small amount of energy necessary to establish the streamer over the previously ionized channel. One or more oscillations may occur within the streamer before the cloud will again discharge into it, finally causing it to reach the earth as a unidirectional pulse.

With 60-cycle applied voltage, streamers are formed on succeeding crests, and are often found to follow similar routes on each succeeding cycle. These streamers have been photographed extending 10 ft. from a pointed electrode.

A recent cathode-ray oscillogram as obtained by the General Electric Company on the lines of the Pennsylvania Power Company showed a voltage wave induced upon the line which started in an oscillatory manner, somewhat above 200 kv., and built up in a transient manner with superimposed oscillations, over a period of 5 microseconds, to a value of 1500 kv. At this point the voltage rose suddenly to 2500 kv., which is explained as an insulator flashover, but may have been a stroke direct or close to the line resulting in the insulator flashover.

The fact that streamers are formed and have such a high conductivity is similar to placing a conducting element close to the cloud, which places the greater portion of the cloud potential at the head of the streamer. The added impulses of voltage as a result of the successive discharges from the cloud into the streamer will account for the long lightning strokes as a result of the rather moderate value of cloud voltage.

Joseph Slepian: (communicated after adjournment) This paper I believe to be the best analysis yet published of the physical occurrences during a lightning flash. I have a few remarks to make which are mostly of a confirmatory nature.

I think it is unfortunate that Mr. Lissman emphasizes the particular voltage gradient of 76 kv. per inch as the one at which cumulative collision ionization begins. The erroneous impression is still widespread in engineering circles that air has a definite critical breakdown gradient of 76 kv. per inch independent of shape and separation of electrodes. This impression seems to be due to the false analogy with failure of materials under mechanical stress, and is quite at variance with experimental facts. Even for plane electrodes, the breakdown gradient varies with electrode separation and may be greater or less than 76 kv. per inch, and for electrode shapes such as points, the maximum gradient at breakdown may be very much greater than 76 kv. per inch.

The part played by space charges during the formation of the flash is very important and is well brought out by Mr. Lissman. Such space charges are neglected in the classical Townsend theory of breakdown between plane electrodes, but in this case their consideration is necessary for understanding of the phenomena. The part played by space charge in breakdown was also pointed out by Professor Loeb, (*Journ. Franklin Inst.*, 1928) and Mr. Torok has recently obtained some corroboratory evidence of the existence of these space charges at the Westinghouse High-Voltage Laboratory.

The development of streamers and conducting filaments as a consequence of high temperature and thermal ionization is an attractive idea, and one which I have used in trying to account for the very great speed of breakdown of spark gaps (*Electrical World*, April 14, 1928, p. 761). I make this thermal ionization come into the picture earlier than Mr. Lissman does, however, as my calculations indicated that sufficiently high temperatures would be reached in the ionizaton path of a single initiating electron. I think this view is supported by the extreme speed with which streamers are formed as in Torok's suppressed discharges.[1]

The explanation given of how very steep wave-front voltage may be induced in a transmission line by a lightning discharge which does not actually strike the line is important, and the need for such an explanation has been felt for some time, since the slow rate of propagation of streamers has been known. To make this explanation complete it is necessary to state that considerable current is flowing in the incompleted streamer. I am happy to say that this last had been experimentally confirmed previous to this paper by Mr. Torok at my suggestion, and we hope to publish these results soon.

J. S. Carroll: Mr. Mendenhall brought up the matter of terms. I am quite in agreement with him in that many of these matters of discussion depend upon the definition of terms. I think the term photoelectric effect comes in here all right, and it could be used in place of some of these others. But I would hesitate myself to alter Mr. Lissman's phraseology, because he has been in the work a little longer than I have.

I should like to emphasize Dr. Ryan's point on the growth of this streamer that we observed in the laboratory. The single streamer from the point appears like a wire extended out with the full voltage on the end and the corona forming out at the end. That is along the line of Mr. Lissman's idea of the lightning stroke. That is one reason why I agree with Mr. Cozzens in the belief that the lightning voltages are not as high as we used to estimate. If you have a cloud above a line at a potential, say, of 10,000,000 volts, then start the streamer down, the streamer is just like a wire pushed down through the cloud when you get near the line. In that case you are subjecting the line to the potential of the cloud almost directly. This is just a theory so far. As pointed out, the matter of electric fields under the clouds is an uncertain variable proposition.

M. A. Lissman: The preceding discussion has shown that it would be advisable to expand some of the concepts advanced in the paper. There, the statement was made that in a conducting streamer ions of both signs are practically equal in number, so that their total effect upon the electric field is zero. It seems to me impossible to escape such a conclusion.

Whatever may be the cause of the high conductivity in a streamer, we know that very large instantaneous currents flow urged by very small voltage gradients. Such a high conductivity necessitates a high concentration of ions. In a metallic conductor we know that the ions are confined with the boundaries of the conductor at ordinary temperature. Incidentally, we know also that within the conductor positive and negative ions offset each other, so that there are no high local electric stresses between adjacent portions of the conductor.

In the case of a conducting filament, we cannot assume that the ions are confined within sharp boundaries. Also we must assume, for the present at least, that each ion can only be affected by the electric gradient prevailing where the ion is located. This gradient is the resultant of all surrounding electric charges. It is a vector quantity having both magnitude and direction. Some authors have published sketches of lightning paths of high conductivity composed only of ions of one sign. We know these paths to be very restricted in cross-section, and if we attempt to determine the gradient affecting these ions, we find that it must have a very high value and be directed radially outward. If such a filament could come into being, it would immediately explode, as we know of no force which could prevent the ions from moving in the direction of the electric gradient. We know that such filaments are stable, and that they have a core of high conductivity and restricted cross-section. We can assume that a sufficient number of ions of one sign move radially outward from the highly conducting core to offset the radial component of the electric field, thus shielding the core. There remains a small longitudinal component which causes enormously large currents to flow in the restricted filament. It does not seem possible to escape the conclusion that ions of both signs must be present in substantially equal numbers in this highly conducting core, thus preventing high local stresses between adjacent portions of the core.

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[1] *Surge Impulse Breakdown of Air*, J. J. Torok, A. I. E. E. Quarterly TRANS., Vol. 47, April, 1928, p. 349.

The objection made by Dr. Slepian against the specific mention of a voltage gradient of 76 kv. per inch being required to produce cumulative collision ionization is well taken. It would have been better to introduce some constant K, specifying that in common with most of our engineering constants it has the habit of varying with the mean free path of the molecules, and perhaps as the result of a number of other causes.

In the present paper the author endeavored to outline that if we assume a sufficiently restricted region of the field, any ordinary time interval which we might use as a unit, such as a microsecond, is long compared to that required to produce collision ionization, and that for a given mean free path the instantaneous gradient is the only factor affecting cumulative ionization. This gradient is the resultant of all surrounding electric charges, but is especially affected by those in the immediate vicinity, which came into being as the result of cumulative collision ionization taking place in the adjacent portions of the field.

When we ordinarily speak of a gradient causing collision ionization for a certain configuration of the electrodes, we mean a hypothetical gradient obtained by dividing the applied voltage by the distance between the electrodes when these are plane, or a mathematical gradient disregarding space charges when they are not. We may consider this applied voltage causing breakdown to be the statistical summation of numerous local breakdowns. We know that it depends to a large extent upon the manner in which space charges are mobilized in the field, and therefore, upon the shape, separation of the electrodes, and the waveform of the stress applied. In the case of large point gaps we are forcibly reminded that conditions in the gap are far from uniform at breakdown. Even in the case of small sphere gaps where we might easily imagine this to be the case, the work recently published by Mr. Torok has shown that it is not so. If we had means of determining the gradient in a restricted portion of the field, the resultant of the distribution of the surrounding electric charges, it is possible that we would discover that cumulative collision ionization becomes effective at a definite electric gradient.

The author cannot entertain at present the idea advanced by Mr. Cozzens of an oscillating streamer whose frequency decreases as it grows in length. It is granted that a streamer has high conductivity and must have inductance. Yet to obtain satisfactory oscillations we must also have capacity in order to transform the kinetic energy of the magnetic field into the potential energy of the electric field. In the present paper the author endeavored to show that before any reasonable amount of electricity could be stored at the end of a streamer, this streamer had to branch out many times with increasing resistance in the branches, and that the final charges are deposited through the process of collision ionization. This introduces sufficient series resistance to cause critical damping. There can be no energy stored by a convection current of ions, as by definition of ion mobility we assume that the energy made available by the potential through which they fall is immediately transformed into other forms of energy.

I would suggest to Mr. Cozzens that he assume a convenient electric charge to accumulate at the end of a streamer without branching, and then compute the resultant electric field. The values of gradient thus obtained should prove enlightening.

However, the experimental evidence upon which this theory is based is quite interesting. When the development of a 60-cycle flashover is photographed by means of a quartz lens on a rotating film, it is found that the power arc does not immediately follow the enormously rapid condenser discharge. Rather, several condenser discharges succeed each other at a definite frequency, following the same path.

I am tempted to give a widely different explanation from that advanced by Mr. Cozzens. There is a certain amount of energy stored as a displacement current between the transformer terminals, and between these and the ground. This energy stored in the electric field is immediately available when breakdown culminates into a condenser discharge, as the series inductance is quite low. The resultant temperature in the streamer is very high, but as the filament is still very restricted, it cools rapidly. As soon as the condenser is discharged, the current in the streamer dies down and it begins to cool. The transformer terminals are now discharged, and due to the large value of leakage reactance in the secondary, it takes an appreciable time to restore the charging current to the terminals. During this charging time the filament has cooled sufficiently so that the succeeding discharge, although following the same path, is not yet a power arc, but another condenser discharge. This takes place several times over each crest. In the meantime heat diffuses radially outward from the filament, and finally the volume of heated air is sufficient to prevent rapid cooling and true arc conduction is initiated.

Thus, a condenser discharge is caused by a streamer lengthening by successive breakdowns due to a very high gradient at its growing end, resulting in a high average gradient, while the arc discharge has a low average gradient. The arc does not grow by successive breakdown, but imitates metallic conduction in that a sufficient supply of ions is available to carry the current.

Heat Flow from Underground Electric Power Cables

BY NEIL P. BAILEY[1]

Non-member

Synopsis.—The heat resistance of the soil surrounding underground cable ducts is usually large, and the path of the heat through the soil is not simple, especially when there are several adjacent ducts. This heat resistance and the path of the heat flow may be determined graphically, but except in the simpler cases, this method becomes very difficult.

The heat resistance of any one of several ducts can be calculated theoretically by making assumptions of unknown magnitudes. To check these calculations by testing actual installations would be slow and expensive. Advantage may be taken of the similarity between the flow of heat and the flow of electricity to set up and test the electrical equivalent of any duct system. In this way the theoretical results can be checked readily with a minimum outlay of equipment.

Results obtained by this method show the theoretical calculations to be accurate even for close spacing and also give a picture of the actual path of the heat from a group of several ducts. Thus, the heat resistance of a duct may be found quite accurately if the specific heat resistance of the soil is known.

OBJECT

SINCE the current carrying capacity of an underground electric power cable is usually limited by heating, it is desirable to understand the manner in which this heat is dissipated. It must obviously pass through the cable insulation and sheath and across the air-space to the duct. Up to this point the path of the heat is quite definite and it is not affected by surrounding cables. However, after the heat leaves the duct, its path is not so obvious, and the heat flow from one duct is affected by that from adjacent ones.

It is the object of this paper to present experimental verification of theoretical methods of calculating the heat resistance of the earth surrounding underground cable ducts.

SYMBOLS

Q = Rate of heat flow per unit length of duct
T = Temperature
r = Duct radius
p = Any radial distance from the center of a duct
S = Specific heat resistance
C = Specific heat capacity
t = Time
d = Depth of a duct below the ground surface
l = Spacing between duct centers
R = Heat resistance per unit length of duct.

DIRECTION OF HEAT FLOW

The study of the heat flow from the ducts is facilitated by considering them as new cylindrical heat sources. Also, it is usually permissible to assume that the ducts are buried directly in the soil, since the heat resistance of the materials in which the ducts are commonly set is very close to that of most soils. (See Appendix B.)

In the case of a duct whose length is great compared with its diameter, it is evident that the heat will flow out radially into the soil. However, since the surface of the ground is within a few feet on one side, and there is an infinite extent of earth on the other, the heat will not flow out uniformly in all radial directions.

An idea of this heat distribution may be obtained by studying the heat flow from a duct surrounded by an infinite extent of soil in all radial directions.

Consider an annular ring of soil of specific heat resistance S and thickness $d\,p$ at a distance p from the center of the duct, of radius r. The heat resistance of this ring per unit length is given by,

$$d\,R = \frac{S\,d\,p}{2\,\pi\,p} \qquad (1)$$

Since the soil extends an infinite distance in all radial directions, the total heat resistance per unit length of duct is,

$$R = \int_r^{00} \frac{S\,d\,p}{2\,\pi\,p} = \frac{S}{2\,\pi} \log_e \frac{00}{r} = 00 \qquad (2)$$

From this, it is evident that in the case of an actual duct, no heat will flow downward after the transient period is over, for to do so it would have to flow into an infinite extent of soil.

The objection might be raised that since the heat capacity of the earth is infinite, steady state conditions will never be realized. However, in Appendix A, the heat capacity of the soil is considered and the transient period is shown to be over in a relatively short time.

GRAPHICAL METHOD OF CALCULATING HEAT RESISTANCE

Knowing that all of the heat from a linear underground heat source flows to the surface of the earth, it is possible to solve for the heat resistance graphically. As shown by Fig. 1, the ground surface may be considered as an equi-temperature surface. Other equi-temperature surfaces may then be drawn in arbitrarily. Lines of heat flow must cross these surfaces at right angles, for otherwise heat would be flowing without an accompanying temperature drop. If the rectangles between equi-temperature surfaces and lines of flow are squares, ($m = n$ in Fig. 1) and if the plot is for a unit length of source, the resistance of each square is numerically equal to the specific resistance of the soil. The resistance of each tube may be found from the number of squares in series, and the total resistance from the number of tubes in parallel.

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[1] Assistant Professor of Mechanical Engineering, University of Idaho, Moscow, Idaho.

Presented at the Pacific Coast Convention of the A. I. E. E., Spokane, Wash., Aug. 28-31, 1928.

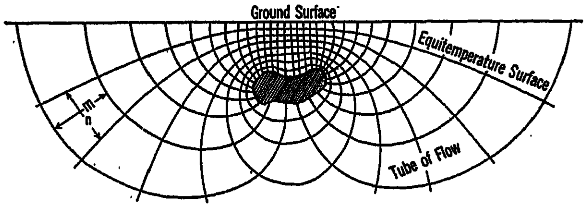

FIG. 1—GRAPHICAL METHOD OF CALCULATING THE HEAT RESISTANCE FOR ANY LINEAR UNDERGROUND HEAT SOURCE

This field plot is found by the method of trial and error, but only one solution exists. Lines of flow and equi-temperature surfaces must be drawn in and adjusted until the correct solution is obtained. In the example shown, the resistance of each square is S, the specific heat resistance of the soil. There are eight squares per tube, giving a resistance per tube of $8\,S$. There are 29 tubes in parallel, giving a total resistance per unit length of source of $8\,S/29$.

The beauty of this method is that it is independent of the cross-section of the source, as indicated in Fig. 1. The chief difficulty is that it becomes increasingly tedious as the number of ducts is increased.

THEORETICAL EQUATIONS FOR CYLINDRICAL SOURCES

Theoretical expressions for the heat resistance of underground ducts may be derived as follows:

The heat flow from a line source to the earth's surface may be represented by the lower portion of Fig. 2 which is a line source from which the rate of heat flow is $+ Q$, per unit length of source. If the earth's surface is considered as a zero temperature plane, this same field of flow may be realized by replacing the ground surface by an image of the line source at an equal distance above the surface. If the heat flow from the image is $- Q$ and the system is placed in the soil, the plane previously occupied by the surface of the ground will remain a zero temperature surface, and the heat flow from the original line source to this surface will be the same as before (see Fig. 2).

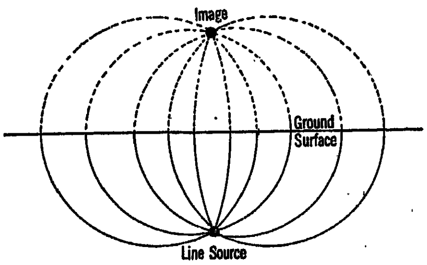

FIG. 2—GROUND SURFACE REPLACED BY THE IMAGE OF A LINE SOURCE

Making use of the principle of superposition, the temperature difference between any point and the zero temperature surface is that which the point would have due to the heat flow $+ Q$ leaving the line charge radially and undistorted, plus that due to the heat $- Q$ flowing radially from the image.

Consider the point A in Fig. 3. When only the line source with a flow per unit length of $+ Q$ is acting, the heat flows radially. The temperature drop across an annular ring of thickness $d\,p$ at a distance p from the source is,

$$\frac{Q\,S}{2\,\pi\,p}\,d\,p$$

The temperature difference between A and the zero temperature surface is,

$$\Delta\,T_1 = \int_{d_1}^{h} \frac{Q\,S\,d\,p}{2\,\pi\,p} = \frac{Q\,S}{2\,\pi}\log_e \frac{h}{d_1} \qquad (3)$$

In a similar manner, the difference in temperature between A and the zero temperature surface due to the flow $- Q$ from the image acting alone is,

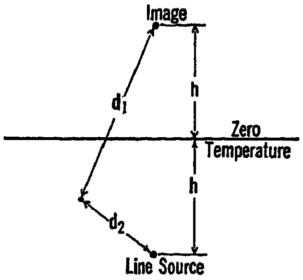

FIG. 3

$$\Delta\,T_2 = \int_{d_2}^{h} \frac{-\,Q\,S}{2\,\pi\,p}\,d\,p = \frac{-\,Q\,S}{2\,\pi}\log_e \frac{h}{d_2} \qquad (4)$$

Thus, the temperature difference for both acting simultaneously is the sum of these two, or

$$\Delta\,T = \frac{Q\,S}{2\,\pi}\left[\log_e \frac{h}{d_1} - \log_e \frac{h}{d_2}\right]$$

$$= \frac{Q\,S}{2\,\pi}\log_e \frac{d_2}{d_1} \qquad (5)$$

So far, only a line source has been considered, and the actual case is that of a cylindrical heat source. By neglecting distortion, the line source may be considered as being at the center of the duct, and the duct surface will be approximately an equi-temperature surface. This assumption could be avoided by further refinement, but it was not found to be necessary.

Upon this basis, the temperature of the duct surface above the temperature of the ground surface for a duct of radius r buried at a depth d becomes,

$$\Delta T = \frac{Q\,S}{2\,\pi} \log_e \frac{2\,d}{r} \qquad (6)$$

The resistance R per unit length of duct is,

$$R = \frac{\Delta T}{Q} = \frac{S}{2\,\pi} \log_e \frac{2\,d}{r} \qquad (7)$$

In a similar manner, the heat resistance per unit length for any duct arrangement may be calculated. The temperature of any duct above that of the ground surface is the sum of the temperature differences due to the heat flow of each duct and image acting alone. Appendix C gives the theoretical equations for three and six ducts.

Since in these theoretical equations all effects of distortion are neglected, it is the chief aim of this paper to investigate the accuracy of such equations.

Experimental Verification of Theoretical Equations by Electrical Analogy

The laws governing the flow of heat are the same as those governing the flow of electricity, and the only difference between the equations of the two is one of units. The equations for the flow of heat through the soil are exactly similar to the equations for the flow of d-c. electricity through a conducting solution.

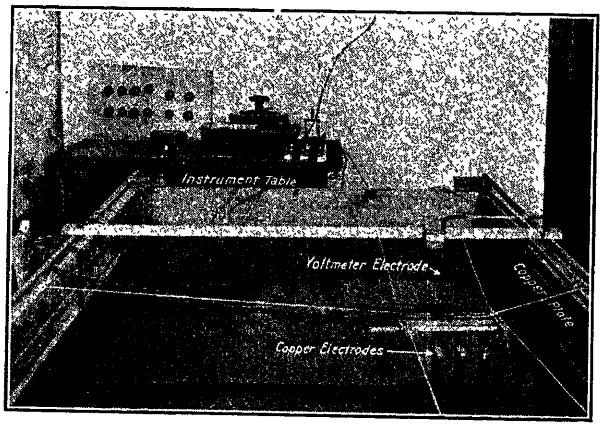

Fig. 4—Electrical Test Tank

Advantage was taken of this fact to check experimentally the theoretical equations previously derived. To run a comprehensive set of tests on actual cable installations would be a slow and expensive procedure, while the equivalent electrical circuits can be set up and tested very readily.

The heat system is represented in the following manner. A unit length of the duct and its surrounding soil may be replaced by a rectangular wooden box containing ordinary tap water. (See Fig. 4.) Since the heat all flows to the surface of the earth, the ground surface may be replaced by a copper plate along one vertical side of the box, the remainder of the box being waxed to insure its insulating qualities.

A length of duct is represented by copper tubing set vertically in the water. The temperature difference between the cable and the earth's surface may be replaced by a d-c. voltage between the copper plate and the copper tubing, and the flow of electricity replaces the heat flow.

If the electrical system is constructed with the ratio of depth of electrode from the plate to radius of electrode which corresponds to the ratio of depth of duct to radius of duct, an electrode in one foot depth of water in the tank will completely represent a one foot length of duct. If, then, a d-c. voltage is applied and the current measured, the electrical resistance of the system may be calculated.

By measuring the specific electrical resistance of the water in ohms per ft. cube, and dividing this into the resistance per unit depth of water, the electrical resistance coefficient (R/S), (ratio of resistance per unit length to specific resistance), may be found.

Now, since the flow of heat through the soil is governed by the same laws that govern the flow of electricity through the solution, and since the units of R/S are independent of system considered, the R/S for the heat system is exactly the same as the R/S for the equivalent electrical system. In this way it is possible to obtain an experimental check on the theoretical equations previously derived.

In running these tests it was necessary to take certain precautions to insure accurate results. In the first place, in order that the flow of electricity through the water would correspond to the flow of heat through the soil, it was necessary to limit the current density to such values that there would be no disturbing convection in the water due to heating and violent gassing at the electrodes. This limit was readily found by observation.

In the second place, it was necessary to devise some means of eliminating the error due to surface voltage drop between the electrodes and the water. This film resistance varies rapidly with changes in current density, gassing, and the condition of the surface of the electrode.

Careful investigations indicated that this film voltage drop all occurs in a very short distance from the surface of the electrode. It was also found that even when the electrode was quite close to the plate, the voltage was essentially constant around concentric surfaces for a distance of from 1/10 to 2/10 of an in. from the smallest electrode used. In addition, it was found that the surface voltage drop at the plate was entirely negligible due to the large area.

In the light of the foregoing investigations, it was decided to measure voltage between the plate and a point 1/10 of an in. in a radial direction from the surface of the electrode under consideration, and compensate for this by considering the radius of the electrode to be 1/10 in. greater. Thus, all readings were independent of the surface voltage drop which varied from 2 to 10 volts depending on conditions. In this manner, an electrode 5/10 of an in. in diameter became 7/10 of an in. in diameter in the results.

The voltage was measured at 1/10 in. radially from the electrode by using a fine copper wire which protruded a short distance out of a small glass tube. The end of the tube was surrounded by a ring of 1/10 in. radius. Thus, when the ring on the rod was held in contact with the electrode surface, the copper wire voltmeter terminal was exactly 1/10 in. from the surface of the electrode. The fact that the voltmeter electrode projected only a short distance out of the glass tube made it possible to read the voltage at any depth in the water. In this way it was found that the flow was uniform at all depths for a given point.

This exploring electrode was mounted on a bar which extended across the tank, and which was mounted on longitudinal ways. Thus, the bar could be moved along the tank, and the electrode could be moved along the bar. By calibrating the longitudinal ways and the bar in feet, tenths, and hundreds, measuring the center of coordinates from the center of the plate, the voltage at any point in the tank could be recorded directly in its rectangular coordinates.

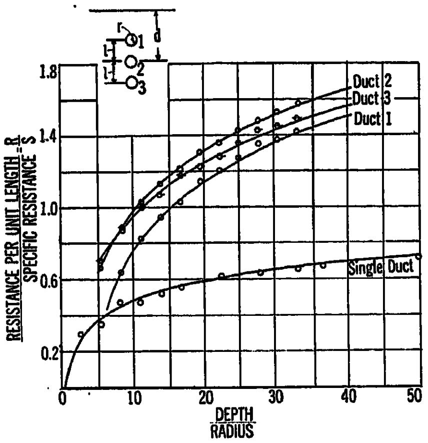

Fig. 5—Resistance Coefficient (R/S) for a Single Duct and for Three Ducts, Spaced Vertically as Shown for $l/r = 4$

Theoretical curves and experimental points shown

Further investigation showed that the voltage readings given by a high-resistance voltmeter checked within one per cent of the readings given by a potentiometer, thus making it possible to speed up the work by using a high-resistance, direct-reading voltmeter instead of a potentiometer. A low-resistance voltmeter could not be used because the current drawn by it would be great enough to cause the exploring electrode to act as an auxiliary current electrode, thus distorting the flow.

As a final precaution, any electrical potential due to battery action was eliminated by having no metal in the water except high grade copper. Any possibility of ground current through the box and floor was eliminated by using a generator and lines which were carefully insulated from the ground.

All specific electrical resistance measurements were made by means of a carefully calibrated, bridge type, Leeds-Northrup cell. Determinations were made at the beginning and end of each test, and were made at the temperature corresponding to the temperature of the water during the test.

The electrical equivalent of one, three, and six ducts was set up and tested, and the values of a resistance coefficient R/S were found for various values of d/r.

Those experimental points are shown plotted in Fig. 5 and Fig. 6, together with the theoretical curves for the same conditions as derived in Appendix C. The experimental data are given in Appendix D.

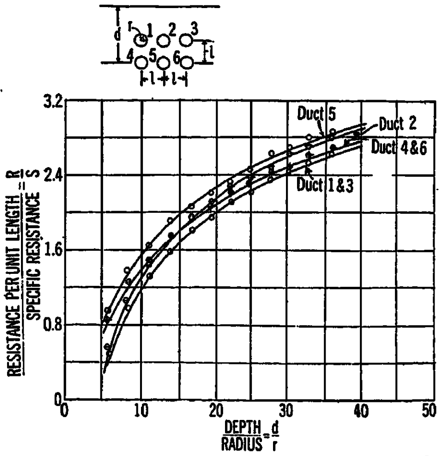

Fig. 6—Resistance Coefficient (R/S) for Six Cables Spaced Horizontally in Two Rows

Theoretical curves and experimental points shown for $l/r = 4$

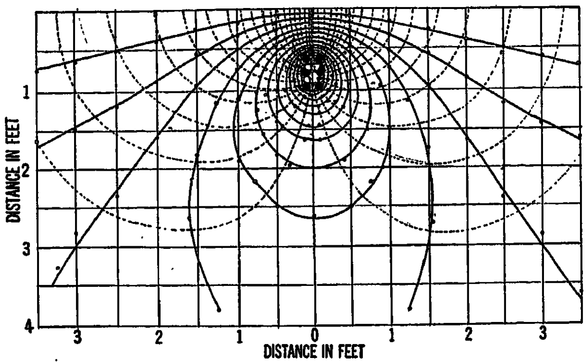

Fig. 7—Flow from Six Electrodes

Equivoltage surfaces—full lines

Lines of flow—dotted lines

As shown by the curves, the theoretical equations and experimental points check quite satisfactorily, showing that the distortion caused by close spacing of the electrodes does not cause appreciable error in the theoretical equations.

Verification of Graphical Method

In order to check the graphical method and to study the field of flow from six ducts, the equivalent electrical circuit was built up and every second equi-voltage surface was plotted from data obtained by means of the exploring voltmeter electrode. The lines of flow were then sketched in at right angles with the equi-voltage surfaces so that the intersected areas were approximate squares. This is shown in Fig. 7. It might be of interest to note the manner in which the flow is forced to leave the lower four electrodes and the large area between them through which practically nothing seemed to flow.

For this set-up, six 0.36-in. radius electrodes were spaced 2.16 in. on centers, the center row 9.6 in. from the plate in 1.5 ft. of water having a specific electrical resistance of 123 ohms per ft. cube. For a current of 0.15 amperes per electrode, the voltage of the two top electrodes was 24 volts, and 28 volts for each of the other four.

The lines of flow as drawn give approximately six tubes of flow per electrode. The following is a comparison of the graphical test, and theoretical methods of obtaining the resistance.

Electrodes 1 and 2:

Graphical—$R/S = 12/6 = 2.0$

Test $$R/S = \frac{24}{123} \cdot \frac{1.5}{0.15} = 1.96$$

Theoretical, from equations in Appendix C,
$$R/S = 2.03$$

Cables 3, 4, 5, and 6,

Graphical $R/S = 14/6 = 2.33$

Test, $$R/S = \frac{28}{0.15} \cdot \frac{1.5}{123} = 2.27$$

Theoretical, $R/S = 2.25$

This seems to indicate a reasonable consistency in the results obtained by the various methods.

CONCLUSIONS

On the basis of the foregoing results, it does not seem unreasonable to state that the heat resistance of any one of a number of ducts may be calculated theoretically with confidence. As stated earlier in the paper, the error involved in assuming that the ducts are buried directly in the soil is small and on the safe side, because the heat resistance of the concrete in which the ducts are set is less than that of most soils.

The fact that the cables lie in contact with the bottom of the ducts may cause the temperature of the bottoms of the ducts to be higher than that of the tops, and thus violate the assumption that the ducts are equi-temperature cylinders. However, it is difficult to believe that this could cause serious distortion.

Throughout the discussion it has been assumed that the ground surface is an equi-temperature plane. This is not strictly true, since it will be at a higher temperature directly over the duct than it is farther away. This effect is quite small except when the ducts are extremely close to the surface.

The expression for temperature of any duct of a group having different values of heat flow may be found by using a system of images in a manner exactly analogous to that used when the ducts dissipate the same amount of heat. However, the temperature of any one duct can be found only by knowing the heat flow from each duct, and the solution will be more involved.

Enough data exist to determine the specific heat resistance of most soils encountered so it seems entirely justifiable to calculate the heat resistance for the ordinary arrangements of underground power cables by the theoretical method.

Appendix A

TRANSIENT HEAT FLOW FROM A LONG CYLINDER IN AN INFINITE EXTENT OF SOIL

The effect of the heat capacity of the soil may be best studied by considering the transient heat flow from a cylinder of radius r buried in an infinite extent of soil having a specific heat resistance S and heat capacity C.

If the heat flow per unit length of cylinder at any radial distance p and time t is Q, the temperature drop across an annular ring of radius p and thickness $d\,p$ is given by:

$$\frac{\partial T}{\partial p}\, d\,p = \frac{Q\,S}{2\,\pi\,p}\, d\,p \tag{8}$$

The rate of heat storage in the ring is:

$$\frac{\partial Q}{\partial p}\, d\,p = 2\,\pi\,p\,C\,\frac{\partial T}{\partial t}\, d\,p \tag{9}$$

Combining equations (8) and (9)

$$\frac{\partial^2 T}{\partial p^2} + \frac{1}{p}\,\frac{\partial T}{\partial p} - C\,S\,\frac{\partial T}{\partial t} = 0 \tag{10}$$

Replacing $\partial/\partial t$ by Heaviside's operator P and integrating with respect to p in a series,

$$T = a_0 \left[1 + \frac{S\,C\,P\,p^2}{2^2} + \frac{(S\,C\,P)^2 p^4}{2^2 . 4^2} + \frac{(S\,C\,P)^3\, p^6}{2^2 . 4^2 . 6^2} \text{ etc.} \right] \tag{11}$$

Making use of the terminal conditions at the cable where $p = r$ and $T = T_0\,1$, equation (11) becomes:

$$T = T_0\,1 \left[\frac{1 + \frac{S\,C\,P\,p^2}{2^2} + \frac{(S\,C\,P)^2\,p^4}{2^2 . 4^2} + \frac{(S\,C\,P)^3\,p^6}{2^2 . 4^2 . 6^2} \text{ etc.}}{1 + \frac{S\,C\,P\,r^2}{2^2} + \frac{(S\,C\,P)\,r^4}{2^2 . 4^2} + \frac{(S\,C\,P)^3\,r^6}{2^2 . 4^2 . 6^2} \text{ etc.}} \right] \tag{12}$$

In Heaviside's notation, $T_0\,1$ represents a square wave of temperature applied at time $t = 0$ and remaining constant. It is the same as saying that at time $t = 0$ the temperature of the cable is raised T_0 degrees above the initial temperature of the surrounding earth. A square wave of heat flow $Q_0\,1$ would more nearly represent the true case of a cable, but the solution for that gives rise to an indeterminant solution.

From equations (8) and (12):

$$Q = \frac{2\,\pi\,p}{S}\,\frac{\partial T}{\partial p} = \frac{2\,\pi\,T_0\,1}{S}$$

$$\left[\frac{\dfrac{S\,C\,P\,p^2}{2} + \dfrac{(S\,C\,P)^2\,p^4}{2^2\,.\,4} + \dfrac{(S\,C\,P)^3\,p^6}{2^2\,.\,4^2\,.\,6}\text{ etc.}}{1 + \dfrac{S\,C\,P\,r^2}{2^2} + \dfrac{(S\,C\,P)^2\,r^4}{2^2\,.\,4^2} + \dfrac{(S\,C\,P)^3\,r^6}{2^2\,.\,4^2\,.\,6^2}\text{etc}}\right] \tag{13}$$

This is in Heaviside's form, $Q = \dfrac{2\,\pi\,T_0\,1}{S}\,\dfrac{Y\,(P)}{Z\,(P)}$ (14)

And the solution is:

$$Q = \frac{2\,\pi\,T_0}{S}\left[\frac{Y\,(0)}{Z\,(0)} + \sum \frac{Y\ (P)\ e^{Pt}}{P\,\dfrac{d\,Z\,(P)}{d\,P}}\right] \tag{15}$$

The summation being evaluated for each root of $Z\,(P) = 0$. $Y\,(0)$ and $Z\,(0)$ are found by substituting $P = 0$ in $Y\,(P)$ and $Z\,(P)$.

$$\frac{Y\,(0)}{Z\,(0)} = \frac{0}{1} = 0 \tag{16}$$

$$Y\,(P) = \frac{S\,C\,P\,r^2}{2} + \frac{(S\,C\,P)\,r^4}{2^2\,.\,4} + \frac{(S\,C\,P)^3\,r^6}{2^2\,.\,4^2\,.\,6}\text{ etc.} \tag{17}$$

$$Z\,(P) = 1 + \frac{S\,C\,P\,p^2}{2^2} + \frac{(S\,C\,P)^2\,p^4}{2^2\,.\,4^2} + \frac{(S\,C\,P)^3\,p^6}{2^2\,.\,4^2\,.\,6^2}\text{etc.} \tag{18}$$

$$P\,\frac{d\,Z\,(P)}{d\,P} = \frac{S\,C\,P\,p^2}{2^2} + \frac{(S\,C\,P)^2\,p^4}{2^2\,.\,4\,.\,2} + \frac{(S\,C\,P)^3\,p^6}{2^2\,.\,4^2\,.\,6\,.\,2}\text{ etc.} \tag{19}$$

From a table of Bessel's functions, the roots of $Z\,(P) = 0$ are:

$$P_1 = -\frac{5.78}{S\,C\,p^2} \qquad P_5 = -\frac{223}{S\,C\,p^2}$$

$$P_2 = -\frac{30.5}{S\,C\,p^2}, \qquad P_6 = -\frac{326}{S\,C\,p^2}$$

$$P_3 = -\frac{75.0}{S\,C\,p^2} \qquad P_7 = -\frac{450}{S\,C\,p^2}$$

$$P_4 = -\frac{103.8}{S\,C\,p^2} \qquad P_8 = -\frac{591}{S\,C\,p^2}$$

Since only the heat flow at the cable is desired, equation (**5**), will be evaluated directly for $p = r$ where $Q = Q_0$.

For $p = r$ $\quad \dfrac{Y\,(P)}{P\,\dfrac{d\,Z\,(P)}{d\,P}} = 2$ for all values of P.

Equation (**15**) becomes:

$$Q_0 = \frac{4\,\pi\,T_0}{S}\left[\,e^{-\frac{5.78\,t}{S\,C\,r^2}} + e^{-\frac{30.5\,t}{S\,C\,r^2}} + e^{-\frac{75.0\,t}{S\,C\,r^2}} + e^{-\frac{103.8\,t}{S\,C\,r^2}},\ \text{etc.}\ \right] \tag{20}$$

Equation (**20**) gives the rate of heat flow Q_0 per unit length of cable of radius r surrounded by an infinite extent of soil, at any time t after a square wave of temperature T_0 is applied.

Since this equation has no steady state term, it follows that in the case of cables buried underneath the surface of the earth, no heat flows downward into the earth after the transient period is over. Thus, all the heat must then be dissipated at the surface of the ground, even though the heat capacity of the earth is infinite.

Evaluating equation (**20**) for a duct system equivalent to a 1½ ft. diameter cylinder in an infinite extent of average soil will give an idea of the length of the transient period.

Using:

S = 6.5 deg. cent., per watt per ft. cube
C = 12 watt hr. per cu. ft. per deg. cent.
r = 3/4 ft.

Equation (**13**) becomes:

$$Q_0 = 1.92\,T_0\left[e^{-.13t} + e^{-.68t} - e^{-1.69t} + e^{-2.34t} + \text{etc.}\right] \tag{21}$$

Solving equation (**21**) shows that the heat flow drops very rapidly and has practically died out in 24 hr.

Appendix B

The following values for the resistance of various materials may be convenient in connection with this problem:

Material	Resistance in deg. cent. per watt per ft. cube	Authority
Stone concrete	3.5	Physics & Chemistry Handbook
Brick, common red	5.2	Physics & Chemistry Handbook
Dry, clean yellow sand	11.1	G. B. Shanklin
Dry, clean white sand (fine)	13.2	A. E. Kennelly
Dry, yellow sandy soil	12.1	G. B. Shanklin
Clean yellow builders sand—2 per cent moisture	9.2	G. B. Shanklin
Clean yellow builders sand—4 per cent moisture	6.8	G. B. Shanklin
Clean yellow builders sand—6 per cent moisture	4.8	G. B. Shanklin
Clean yellow builders sand—8 per cent moisture	3.4	G. B. Shanklin
Yellow sand clay soil—2 per cent moisture	11.6	G. B. Shanklin
Yellow sand clay soil—4 per cent moisture	11.2	G. B. Shanklin
Yellow sand clay soil—6 per cent moisture	9.7	G. B. Shanklin
Yellow sand clay soil—8 per cent moisture	7.4	G. B. Shanklin
Yellow sand clay soil—10 per cent moisture	5.4	G. B. Shanklin
Yellow sand clay soil—12 per cent moisture	3.7	G. B. Shanklin
Yellow sand clay soil—14 per cent moisture	2.4	G. B. Shanklin

Appendix C

HEAT RESISTANCE FOR MORE THAN ONE DUCT

As previously discussed, it is possible to derive an expression for the heat resistance of any one of a number of ducts by replacing the earth's surface by a system of images and applying the principle of superposition.

Consider three ducts spaced in the vertical a distance l between centers, and the center duct a distance d below the ground surface, each duct having a radius r and a rate of heat flow per unit length of Q. Referring to Fig. 8, the temperature rise of duct No. 1 due to its heat flow acting alone and undistorted is,

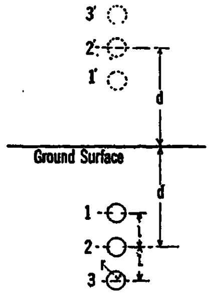

FIG. 8—THREE DUCTS AND THEIR IMAGES

$$\Delta T_1 = \frac{Q\,S}{2\,\pi}\int_r^d \frac{d\,p}{p} = \frac{Q\,S}{2\,\pi}\log_e\frac{(d-l)}{r} \tag{22}$$

The temperature rise of duct 1 due to the heat flow $-Q$ of the image of No. 1 acting alone,

$$\Delta T_1{}^1 = -\frac{Q\,S}{2\,\pi}\log_e\frac{(d-l)}{2\,(d-l)} \tag{23}$$

The temperature rise due to duct 2 acting alone,

$$\Delta T_2 = \frac{Q\,S}{2\,\pi}\log_e\frac{d}{l} \tag{24}$$

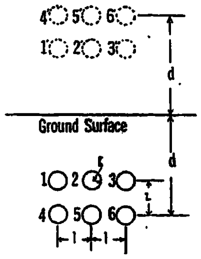

FIG. 9—SIX HORIZONTALLY SPACED DUCTS AND THEIR IMAGES

Due to the image of duct 2,

$$\Delta T_2{}^1 = -\frac{Q\,S}{2\,\pi}\log_e\frac{d}{2\,d-l} \tag{25}$$

Due to duct 3,

$$\Delta T_3 = \frac{Q\,S}{2\,\pi}\log_e\frac{d+l}{2\,l} \tag{26}$$

Due to the image of duct 3,

$$\Delta T_3{}^1 = -\frac{Q\,S}{2\,\pi}\log_e\frac{(d+l)}{2\,d} \tag{27}$$

The total temperature rise of duct 1 becomes the sum of the above, or

$$\Delta T = \frac{Q\,S}{2\,\pi}\log_e$$

$$\left[\frac{(d-l)}{r}\,\frac{(2)\,(d-l)}{(d-l)}\,\frac{(d)}{(l)}\,\frac{(2\,d-l)}{(d)}\,\frac{(d+l)}{(2-l)}\,\frac{(2\,d)}{(d+l)}\right] \tag{28}$$

or,

$$R_1 = \frac{\Delta\ T}{Q} = \frac{S}{2\,\pi}\log_e\left[\frac{(2\,d)}{r}\,\frac{(d-l)\,(2\,d-l)}{l^2}\right] \tag{29}$$

In a similar manner for cable No. 2

$$R_2 = \frac{S}{2\,\pi}\log_e\left[\frac{2\,d}{r}\,\frac{(2\,d)^2-l^2}{l^2}\right] \tag{30}$$

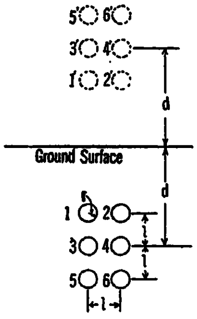

FIG. 10—SIX VERTICALLY SPACED DUCTS AND THEIR IMAGES

and, $$R_3 = \frac{S}{2\,\pi}\log_e\left[\frac{2\,d}{r}\,\frac{(2\,d-l)\,(d+l)}{l^2}\right] \tag{31}$$

For six ducts spaced as shown in Fig. 9,

$$R_1 = R_3 = \frac{S}{2\,\pi}\log_e$$

$$\left[\frac{(d-l)}{r}\,\frac{\sqrt{4\,(d-l)^2+l^2}\,\sqrt{4\,(d-l)^2+4\,l^2}}{\sqrt{10}\,l^2}\right]\text{plus}$$

$$\frac{S}{2\,\pi}\log_e\left[\frac{(2\,d-l)\,\sqrt{(2\,d-l)^2+l^2}\,\sqrt{(2\,d-l)^2+4\,l^2}}{l^3}\right] \tag{32}$$

$$R_2 = \frac{S}{2\,\pi}\log_e$$

$$\left[\frac{(d-l)}{r}\,\frac{[(2\,d-2\,l)^2+l^2]\,[(2\,d-l)^2+l^2]\,(2\,d-l)}{l^5}\right] \tag{33}$$

$$R_4 = R_6 = \frac{S}{2\,\pi}\log_e$$

$$\left[\frac{d}{r}\;\frac{\sqrt{4\,(d)^2+l^2}\;\sqrt{4\,d^2+4\,l^2}\,(2\,d-l)}{\sqrt{10}\;l^3}\right]\text{plus}$$

$$\frac{S}{2\,\pi}\log_e\left[\frac{\sqrt{(2\,d-l)^2+l^2}\;\sqrt{(2\,d-l)^2+4\,l^2}}{l^2}\right] \qquad (34)$$

$$R_5 = \frac{S}{2\,\pi}\log_e$$

$$\left[\frac{d}{r}\;\frac{[(2\,d-l)^2+l^2]\,[2\,d-l]\,[4\,d^2+l^2]}{l^5}\right] \qquad (35)$$

For six cables spaced as shown in Fig. 10,

$$R_1 = R_2 = \frac{S}{2\,\pi}\log_e$$

$$\left[\frac{2\,d}{r}\;\frac{\dfrac{(d-l)\,(2\,d-l)\,\sqrt{4\,(d-l)^2+l^2}}{\sqrt{(2\,d-l)^2+l^2}\;\sqrt{4\,d^2+l^2}}}{\sqrt{10}\;l^5}\right] \qquad (36)$$

$$R_3 = R_4 = \frac{S}{2\,\pi}\log_e$$

$$\left[\frac{d}{r}\;\frac{\dfrac{(2\,d-l)\,(2\,d+l)\,\sqrt{4\,d^2+l^2}}{\sqrt{(2\,d-l)^2+l^2}\;\sqrt{(2\,d+l)^2/+l^2}}}{\sqrt{10}\;l^5}\right] \qquad (37)$$

$$R_5 = R_6 = \frac{S}{2\,\pi}\log_e$$

$$\left[\frac{2\,d}{r}\;\frac{\dfrac{\sqrt{4\,d^2+l^2}\,(2\,d+l)}{\sqrt{(2\,d+l)^2+l^2}\,[d+l]\,\sqrt{4\,(d+l)^2+l^2}}}{\sqrt{10}\;l^5}\right] \qquad (38)$$

Appendix D

EXPERIMENTAL DATA

DATA FOR A SINGLE DUCT PLOTTED IN FIG 5

Conditions: 1.5 ft. depth of water, 0.8 amperes per electrode, specific electrical resistance of water $S = 136.3$ ohms per ft. cube. Effective radius of electrode r 0.36 in.

TABLE I

d (inches)	d/r	Volts	R for 1.5 ft.	R for 1 ft.	R/S
1	2.78	20.7	25.9	38.8	0.285
2	5.66	26.7	32.2	48.3	0.355
3	8.35	31.0	38.8	58.2	0.427
4	11.12	34.5	43.2	64.8	0.476
5	13.90	36.7	45.9	68.8	0.505
6	16.68	40.0	50.0	75.0	0.550
8	22.25	44.0	55.0	82.3	0.605
10	27.80	45.8	57.4	86.1	0.632
12	33.35	48.0	60.0	90.1	0.660

TABLE I—*Continued*

Conditions: 1.5 ft. depth of water, 0.475 amperes per electrode, $S = 136.0$ ohms per ft. cube, effective electrode radius r of 0.136 in.

d (inches)	d/r	Volts	R for 1.5 ft.	R for 1 ft.	R/S
5	36.8	28.5	60.0	90.0	0.662
7	51.5	31.0	65.8	97.8	0.720
9	66.2	33.25	70.0	105.0	0.772

DATA FOR THREE DUCTS SPACED VERTICALLY PLOTTED IN FIG. 5

Conditions: Depth of water 1.5 ft., effective electrode radius $r = 0.36$ in., spacing of electrodes $l = 1.44$ in., $l/r = 4$, $S = 117$ ohms per ft. cube. Amperes per electrode $= 0.25$.

TABLE II

		No. 1		No. 2		No. 3	
d	d/r	Volts	R/S	Volts	R/S	Volts	R/S
2	5.55	7.0	0.359	13	0.666	13.5	0.692
3	8.34	12.5	0.641	17.25	0.885	17.0	0.872
4	11.1	16.25	0.833	20.25	1.038	19.5	1.000
5	13.9	18.5	0.948	22.0	1.128	21.0	1.076
6	16.7	20.25	1.038	23.75	1.215	23.0	1.180
7	19.45	22.5	1.153	25.5	1.305	24.0	1.230
8	22.2	23.5	1.205	26.5	1.36	25.0	1.280
9	25.0	25.0	1.281	28.0	1.435	26.5	1.360
10	27.8	26.5	1.358	29.0	1.485	28.0	1.435
11	30.5	27.0	1.382	30.0	1.538	28.5	1.460
12	33.3	27.75	1.42	31.0	1.59	29.5	1.515

DATA FOR SIX DUCTS IN TWO HORIZONTAL ROWS PLOTTED IN FIG. 6

Conditions: 1.5 ft. of water, $r = 0.36$ in., $l = 1.44$ in., $l/r = 4$ $S = 118.5$ ohms per ft. cube, amperes per electrode $= 0.15$.

TABLE III

		Nos. 1 & 3		No. 2		Nos. 4 & 6		No. 5	
d	d/r	Volts	R/S	Volts	R/S	Volts	R/S	Volts	R/S
2	5.55	6.1	0.515	7.4	0.625	10.3	0.87	11.3	0.955
3	8.35	12.3	1.038	13.8	1.165	14.7	1.24	16.5	1.39
4	11.1	15.6	1.315	17.7	1.495	17.7	1.495	19.5	1.645
5	13.9	18.9	1.515	20.8	1.76	20.8	1.76	22.8	1.935
6	16.7	21.5	1.815	23.2	1.96	23.1	1.95	24.4	2.06
7	19.45	23.1	1.950	25.0	2.11	24.8	2.095	26.5	2.24
8	22.2	25.1	2.120	27.1	2.29	26.4	2.23	27.3	2.30
9	25.0	26.3	2.220	28.1	2.37	27.4	2.32	29.1	2.46
10	27.8	27.9	2.355	30.0	2.43	29.1	2.45	31.4	2.65
11	30.55	29.2	2.46	31.2	2.63	29.5	2.49	32.0	2.70
12	33.3	30.4	2.57	32.4	2.73	31.5	2.66	33.5	2.83
13	36.1	31.3	2.64	33.3	2.81	32.8	2.77	34.3	2.89

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Discussion

R. D. Levy: (communicated after adjournment) I should like to take exception to parts of Mr. Bailey's paper. Mr. Bailey shows that there can be no heat flow from a source, into a medium of infinite dimensions surrounding the source, except during a transient period. He also gives a mathematical demonstration to show that the law for this transient flow variation with time is the sum of a series of decaying exponentials. His relation, as applied to ordinary duct banks, makes it appear that the heat flow into the medium, where the medium is soil, will be negligible after the first few hours. On the basis of the assumption that the transient flow into the earth is of short duration, and may therefore be neglected, the following relation is derived—

$$\Delta T = \frac{Q\,S}{2\,\pi} \log \frac{2\,d}{r}$$

ΔT is the temperature rise of the duct bank surface over earth surface.

This relation may be reduced to an absurdity by making Q zero. Then the temperature of the duct becomes equal to earth surface temperature. We know that under this condition the temperature of the duct is the same as the temperature of ambient earth at duct level.

The correctness of Mr. Bailey's mathematics, where he derives the relation for the decay of heat flow, is questionable. The series which he gives as the solution of the Bessel equation, (10), involves but one arbitrary constant. Inasmuch as this is a differential equation of the second order, it should have two arbitrary constants in its complete solution. The complete solution is,

$$T = (A + B \log C\,S\,P\,p)\left(1 + \frac{C\,S\,P\,p^2}{2^2} + \frac{(C\,S\,P)^2\,p^4}{2^2 \,.\, 4^2} + \,.\,.\,.\,.\,.\right)$$

$$+ B\left(1 - \frac{(C\,S\,P)^2\,p^4}{2^2 \,.\, 4^2}\,\frac{1}{2} - \frac{(C\,S\,P)^3\,p^6}{2^2 \,.\, 4^2 \,.\, 6^2}\left(\frac{1}{2} + \frac{1}{3}\right) - \,.\,.\,.\right)$$

The constants, A and B, must be determined by two known conditions, namely, that when p is r, T is T_o 1, and that when p is infinite, T is zero. Mr. Bailey's solution considers B zero. I have been unable to determine these constants. However, an examination of the results obtained by neglecting B, will show its fallacy. The author assumes a cylindrical duct imbedded in earth of infinite extent, raised to a temperature of T_o at time zero and maintained at that temperature forever after. His derived expression for Q, the heat flow from the cylinder, is shown in his Equation (20). For the special case where S is 6.5, C is 12, r is ¾ ft., and T_o is 10 deg. cent., temperature of undisturbed earth assumed 0 deg. cent., at the end of 20 hours, Q is 1.47 watts by this relation. The resistance to heat flow from the cylinder surface to an imaginary cylindrical surface of 10 feet radius is, from Equation (2),

$$R = \frac{S}{2\,\pi} \log_e \frac{10}{r}$$

For the assumed constants, this resistance is 2.7 deg. cent. per watt. If we assume that all of the 1.47 watts pass through the 10-ft. cylinder or in other words, that none of it goes into storage within the 10-ft. cylinder, we can make a guess at the temperature drop from the duct cylinder to the outside of the 10-ft. cylinder which will be greater than the truth. The actual drop, then, will be less than,

$$2.7 \times 1.47 = 3.97 \text{ deg. cent.}$$

The temperature at the outside of the 10-ft. cylinder will be at least 6.03 deg. cent., and the temperature everywhere within the 10-ft. cylinder will be greater than 6.03 deg. cent. If we multiply 6.03 by 12 (heat capacity of earth) and by the volume of the earth affected, we get 22,700 watthours stored in the 10-ft. cylinder of earth. Of course, this is low since the average temperature is higher than 6.03 deg. cent. If we integrate we get 25,400 watt-hours, which is somewhat more accurate. Now this is only a portion of the heat which has emanated from the duct cylinder in 20 hr., since heat has also been stored in the earth outside of the 10-ft. cylinder which we have been considering. However, if we go back to the author's original expression for heat flow, and integrate directly to find the total heat which has come out of the duct cylinder, we get,

$$Q = 19.2 \int_0^{20} (\epsilon^{-.13t} + \epsilon^{-.68t} + \epsilon^{-1.69t} + \,.\,.\,.\,)\,d\,t = 220 \text{ watt-hours}$$

Thus, by integrating Mr. Bailey's relation, we get 220 watt-hours emitted by the duct cylinder, and by reasoning from the temperature drops computed from the relation, we get in excess of 25,400 watt-hours. Something must be wrong with the relation. Furthermore, the integration process indicates that only 231 watt-hours will be emitted in an infinite time, under the conditions which we have assumed.

We know, of course, that some heat from the duct bank does go down, else the duct bank could never be cooler than street level temperature. I suppose that a correct treatment of the problem of the duct cylinder in an infinite extent of earth would show a transient heat flow of long enough duration to be consistent with observed facts.

A fairly accurate and partially rational expression for duct surface rise over ground level temperature, may be derived by making a simplifying assumption, which is true for all practical purposes. The assumption is, that an equipotential temperature plane exists about 15 ft. below duct level. This plane may be assumed to be at a temperature unaffected by duct heat and by seasonal temperature variations at the earth's surface. The derived relation is not very sensitive to the assumed depth. That is to say, that 10, 15, or 20 ft. may be used with but little effect on the computed results.

Q is the watts loss dissipated from the duct bank, per trench-foot.
S is the soil heat resistivity in deg. cent. per watt, for a foot cube,
h is the height of the duct bank in feet,
w is the width of the duct bank in feet,
d is the depth of the bank below the earth surface in feet (to the center of duct),
T_c is the temperature of the assumed plane. This may be taken as 15 deg. cent. very nearly,
T_s is the temperature of the surface earth. For this, use monthly averages of the air temperatures,—deg. cent.
T_d is the average temperature of the duct bank surface, in deg. cent.

Let
$$A = \log_e \frac{2\,h + 2\,w - \pi\,h + 4\,\pi\,d}{2\,h + 2\,w}$$

$$B = \log_e \frac{2\,h + 2\,w - \pi\,h + 60\,\pi}{2\,h + 2\,w}$$

Then
$$T_d = \frac{\dfrac{Q\,S}{2\,\pi}\,A\,B + T_c\,A + T_s\,B}{A + B}$$

The results obtained with this relation, while not precise, agree fairly well with test data.

N. P. Bailey: This summer conditions at Chelan were such that we could find out some of the temperatures which actually exist. We had an opportunity to run a test of short duration which indicated how in practise the temperatures follow cyclic variations.

The accompanying curves show the results of this test. Each phase current was carried by two 2000-cir. mil lead cables, surrounded by rather coarse, loose sand, which is dry practically all the hot part of the season, the moisture level being considerably lower.

When these cables were installed, arrangements were made to obtain the temperatures during operating conditions. Resistance temperature elements were placed on the outside of the cable lead and the outside of the duct, with the anticipation that those cables would be watched under operation.

At the outset of the test, the load was increased from 1000 amperes to 1600 amperes per phase and held constant during the rest of the time.

The top curve shows the temperature of the middle cable gradually increasing, having a rather sudden increase at first and at the end of the period increasing almost as rapidly as ever. The next curve represents the temperature on the outside of the fiber duct, also increasing, the temperature difference being constant practically all the time, which would be expected, since there was very little chance for heat storage in the duct.

The curve which represents the temperature on top of the concrete structure directly over the center of the cable, rises gradually, and seems to have very much the same rate of increase. In fact, after 12 a. m., within the accuracy of the measurements, there is very little change in the temperature difference between the duct and the concrete, showing that very little heat was being stored in the concrete itself after that time.

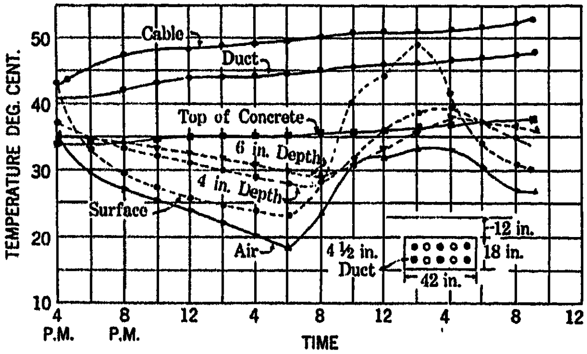

FIG. 1—TEMPERATURE TESTS ON CABLES AT CHELAN

There were two 2000-in. mil cables per phase. The load per phase was 1600 amperes during the test. It had been held at 1000 amperes for a day previous to the test.

The air temperature taken in the shade starts in at 4 p. m. at a temperature in excess of 35 deg. cent., dropping down almost as a straight line until about 6 a. m., when the minimum temperature is obtained, then rising rather rapidly, and falling off again in this same way. That is a typical cycle of the weather there for about four months out of the year. The surface temperature, as would be expected during the night at least, is higher than the air, showing that heat is flowing from the surface; 6 in. down being hotter yet, and the concrete being still hotter than the 6-in. level, showing a very definite temperature gradient for the flow of heat upward.

However, after 8 or 9 a. m. the surface temperature starts up. About 8 o'clock, it became hotter than the 4-in. depth and the 6-in. depth, going up almost to the temperature of the cable, around 4 in the afternoon, then dropping off in the evening. From 8 a. m. until 5 p. m. the surface is hotter than it is down 4 in. deep, which shows definitely that the heat is flowing downward for that first 4 in. From 9 a. m. to 6 p. m. the 4-in. depth was hotter than the 6-in. depth, showing that during that period which started in a little later than the other, the heat was flowing from the 4-in. position downward toward the 6-in. Then for a short period in the afternoon the 6-in. depth became still hotter than the top of the concrete, which showed definitely that heat was flowing toward the concrete. The curves show the successive time lags between the times when the different peaks are reached; the peak of the surface temperature at 2 p. m., the peak on the 4-in. depth at 3:30 p. m., etc. In a rather rough way is shown also the damping of the waves.

We were not able to carry this test to its logical conclusion, but it is hoped that when the opportunity arises we will be able to continue the test for a long enough time to determine more about the cycle of the temperatures. The test was run a little longer than 30 hr. We had obtained data at 1000-ampere load for a day or so before.

In tests run by the Los Angeles Bureau of Light and Power, and which I imagine were for much deeper cables than these because they were on a distribution system, they had curves of temperature which continued to rise for 160 hr., and were still rising at a very substantial rate. So in considering the length of heat transient, it is a different proposition from the electrical transient.

The first point in the discussion of Mr. Levy has already been answered in my closing comments concerning cyclic temperature changes. The question on the accuracy of the transient equations is well taken as in the paper one of the terms of the Bessel function is neglected.

Corrosion of Cable Sheath in Creosoted Wood Conduit

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and

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FOLLOWING the successful use of conduit of creosoted yellow pine in the eastern and southern part of this country, similar duct made of Douglas fir was introduced on the Pacific Coast in 1911. Manufacture was undertaken in the Puget Sound territory; and extensive use of the duct has since been made for both main and subsidiary communication subways in all parts of Washington, Oregon, and California, excepting Southern California where its field has been limited by economical considerations to lateral or subsidiary construction. This conduit was also considered satisfactory, until the latter part of 1923, when corrosion developed on some newly placed telephone cables, and the attending circumstances were such as to indicate that the duct itself might be responsible. It is with the identification of this corrosion and the determination and application of methods of allaying it that this paper is concerned.

Discovery of corrosion presented a problem of some magnitude in so far as the application of palliative measures was concerned. Between 1911, when wood conduit was first introduced on the Pacific Coast, and 1926, when its manufacture for the Bell System was discontinued because of its effect upon the sheath of the cables, approximately 7,250,000 duct ft. were placed as telephone subway; and cables had been pulled into about one-third of it. This problem was simplified to some extent, however, by the fact that the cables had not been affected in all duct runs. There were also approximately 130,000 duct ft. of conduit in the store yards, the salvage of which was, of course, very desirable.

The conduit is made of 4½-in. by 4½-in. sections of timber having a three-in. bore, and mortise and tennon ends. The practise has been to machine it while green, as a rule within five days after the felling of the timber, to overcome the losses which would otherwise occur due to splitting of the duct during the boring process. Until about 1915 the conduit machinery and treating plant were at the same location. Since this date, however, it has been necessary to transport the conduit by barge, from the mill at which it is machined, across Puget Sound to the treating plant. This and other movements of the conduit, which occur between machining and the time it enters the retorts of the treating plant, are made as expeditiously as possible to obviate the checking in thin sections of timber during air seasoning. To avoid this every effort has been made to place the conduit in the retorts within four or five days after it has been machined. Thus, the entire process of manufacture including the felling of the timber and its treatment rarely has exceeded ten days.

Within the period that conduit of this material has been in use, two types of treatment have been employed. The purpose of both of these treatments was to obtain an absorption of 15 lb. of creosote oil per cubic foot of timber by what is known as the "full cell" process, as contrasted with the "empty cell" process, but the movements followed in the application of pressure, heat, and oil have been somewhat different. The creosote oil used with both types of treatment was an imported grade of dead oil of coal tar, or coal tar creosote, and was obtained from the same sources. It has consisted wholly of distillates of gas tar produced by the destructive distillation of bituminous coal, either in the manufacture of coal gas, or in manufacture of coke by the by-product process. So far as is known, the only variation in composition shown by the creosote during the period was in the tar acid content. This has fluctuated to some extent but has never exceeded 10 per cent.

The original process seasoned the wood by boiling it in creosote oil. This operation was followed by application of sufficient temperature and pressure to permit the forcing of the required amount of oil into the duct. In 1916 this method of treatment was superseded by the "vacuum" process which had been developed a short time previously, primarily for use on bridge stringers, etc., the effect upon the fibre strength being decidedly less detrimental. The principal advantages of the new process, as applied to conduit, were that it minimized the losses in treatment from checking and distortion, and presumably resulted in obtaining a better spread of the preservative. Of the latter point, however, there is considerable doubt. With the vacuum process, the wood is immersed in creosote oil and subjected to a minimum vacuum of 20 in. of mercury and to temperatures ranging between 190 deg. fahr. and 200 deg. fahr. until the moisture content is reduced to approximately the fibre saturation point, after which pressure is applied until the timber has absorbed the required amount of oil. At the end of the pressure period the retorts are emptied of preservative, and a vacuum of 20 in. of mercury created for about two hours, under an average temperature of 160 deg. fahr. The entire treating process consumes about 20 hr. on an average, and is of somewhat longer duration than the earlier process.

In the light of more recent experience it has become apparent that cable failures due to corrosion by creo-

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soted wood conduits occurred prior to 1923, but were at the time attributed to other causes. The first case which can be ascribed with any assurance to creosoted wood occurred at Yakima, Washington in 1921. Even as late as 1925, however, it was not certain that the trouble was associated with the conduit. The fact that creosoted wood had not been known previously to cause corrosion, that there had been no change in the wood or creosote used in the manufacture of conduit, that other users of creosoted wood conduit had not reported trouble, all tended to absolve the conduit. The change in the method of creosoting introduced in 1916 was not such as to arouse suspicion, and moreover so far as was known, corrosion did not follow immediately after the change in process. When late in 1923 serious cases of corrosion occurred first in Seattle and then in San Francisco and elsewhere on the Coast it became evident that the action was not due to the soil as was suspected at first. A study of soil samples from the points of failure also had given no indication of unusual acidity. It was recognized that the trouble could not be due to electrolysis since its occurrence bore no relationship to the potential condition of the cable with respect to earth and since perforation of the sheath occurred on the top or sides of the cable which were not in contact with the duct, and then only in duct runs which were free from water and well drained. Corrosion was never experienced on cables which were submerged in water continually or for a part of the year. On the other hand, the action was facilitated by the condensation of moisture in the form of droplets on the cable. That climatic conditions, particularly temperature and humidity, were important is seen in the fact that in the region of Seattle, corrosion was rapid only in the Spring and Fall, whereas in San Francisco it occurred at much the same rate the year around. The alloy used for cable sheath in recent years consisted of 99 per cent lead and 1 per cent antimony, and the question arose as to whether the sheath suffering corrosion was of normal composition. Chemical and microscopic analysis, however, showed it to be of the composition specified and not abnormally susceptible to corrosion.

Corrosion of the type experienced manifests itself by the formation of a white encasement around the globules of moisture condensed on the sheath. In the early stages a mottled effect is produced, but as the attack progresses, the surface of the cable, particularly the top and sides, becomes heavily coated with a white encrustation of lead carbonate or basic carbonate, as is shown in Fig. 1. Chemical analysis of this product gave an indication also of the presence of volatile organic acids. Beneath the carbonate coating the sheath was pitted corresponding to the original globules of moisture. It was perforation of the sheath by these pits which led to failure of the cables. In one instance an 18-in. section of sheath displayed seven perforations.

The persistence of corrosive conditions with time has been a matter of great interest. Observations have indicated that the corrosive qualities of the conduit become depreciated with time and are influenced to some extent by conditions of ventilation, its exposure to the weather before installation in the ground, etc. A recent analysis of the corrosion failures in one locality has shown that about 70 per cent of the failures occurred on cables which had been under ground for less than 15 months, and furthermore, that about 90 per cent of the failures occurred in conduit which at the time the cables were placed in it had been in the ground for less than 13 months. In mitigation of these facts it should be pointed out that possibly sufficient time had not elapsed for many cases of the less active corrosion to reveal themselves and further, that in most cases the conduit was laid for immediate occupancy and service conditions have not been such as to warrant the later installation of cables, the performance of which would indicate the persistence of corrosive conditions.

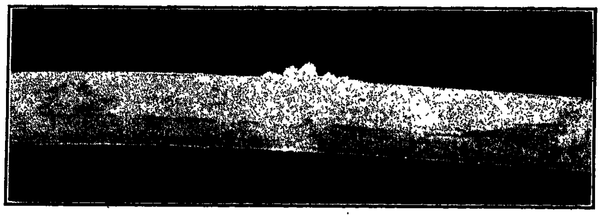

Fig. 1—White Carbonate Formed on Lead Cable Sheath

The volatile nature of the corroding agent was evident from the fact that the corrosive action in many cases extended into the manhole beyond the mouth of the ducts. This was particularly noticeable in manholes situated on hillsides where the action was visible on cables leading into the manhole from the lower side, but was not discernible at the mouth of the ducts on the side leading up-hill.

A careful consideration of the facts disclosed by field observations led to the conclusion that the most likely cause of corrosion was to be sought in the high proportion of carbon dioxide and other acid vapors in combination with humidity changes in the duct atmosphere. It had been shown previously that the characteristic attack could be imitated in the laboratory by exposing pieces of cable sheath bearing drops of water to moist air containing carbon dioxide and a trace of acetic acid vapor. A more quantitative method of determining the rate of corrosion so produced was developed later and consisted in the measurement of the rate of increase in electrical resistance of extruded lead wires which resulted when these wires were reduced in cross-section by the progress of corrosion. This method was particularly useful later in testing the effectiveness of various palliative treatments.[3]

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[3] The development of this method of measuring corrosion rates was due to W. A. Hyde and W. E. Campbell of the Bell Telephone Laboratories and will be described in more detail in a later paper.

Having concluded that the corrosion was definitely associated with vapors present in the duct it became desirable to investigate the composition of duct air where corrosion was actually in progress and for this purpose a portable apparatus was developed. It consisted essentially in an aspirator, a trap for freezing out volatile vapors, a thermal conductivity cell with a Wheatstone bridge arrangement for measuring carbon dioxide, and wet and dry bulb thermometers for determining the humidity. The aspirating device was a small mechanical pump and was driven by a motor which was operated on a six-volt storage battery. Capillary flow meters were used to measure the flow of air from the duct. The most suitable rate of air-flow was found to be from 9 to 11 cu. in. per min. The temperature of the vapor trap was maintained near –110 deg. fahr. by surrounding it with solid carbon dioxide. An auxiliary set of vapor traps made it possible to study the air from four ducts simultaneously. The apparatus was mounted generally on a truck which, during a test, was parked beside a manhole. Glass tubes led from the apparatus to the ducts. The conductivity cell was calibrated for the range 0.1 to 20.0 per cent carbon dioxide and the values could be read to 0.05 per cent. The substances obtained in the vapor trap were analyzed in the laboratory for tar acids and acids of the acetic type and tests were made for aldehydes, sulphur compounds, nitrates, and chlorides.

After preliminary work with this apparatus in New Jersey had shown it to be suitable for the purpose, it was taken to the Pacific Coast and used at Seattle, Tacoma, Portland, San Francisco, Oakland, and Los Angeles. In the 25 runs which were made there were included both corrosive and non-corrosive creosoted wood ducts, tile ducts, and fibre ducts. Some of the ducts contained cables and others had never been occupied. In one case the apparatus was set up in a central office cable vault and operated continuously for three days on a bank of corrosive ducts which led into that office. Most of the wood conduit studied had been placed since 1920 but in two cases it dated from 1914. Finally runs were made at the creosoting plant which had manufactured the conduit, vapors being collected from the air in the work-storage and condensate tanks.

The results of these tests showed that small amounts of a volatile organic acid, probably largely acetic acid, were present in the air in creosoted wood ducts which had been installed in recent years, and that in general, the higher concentrations of acid were found in the more corrosive sections. Although the actual concentration of acid calculated as acetic acid did not exceed 0.1 mg. per cu. ft. of air, previous laboratory investigations had shown that acid concentrations of this magnitude were definitely corrosive to cable sheath. The runs made at the creosoting plant revealed the presence of still greater concentrations of acid in storage tank air, the values being from two to four times greater than those found in conduit air.

Tar acids and naphthalene were collected in considerable quantities from the creosoted wood ducts, but neither of these substances, nor carbon dioxide, within the limits found, 0.1 per cent to 6.0 per cent, bore any relationship to the corrosive action. Nor did these substances show in laboratory tests, the marked corrosive action displayed by traces of acetic acid.

In the meantime, additional laboratory tests had shown that green Douglas fir wood contains considerably larger quantities of volatile acid than does southern pine or western hemlock and that the corrosive qualities of sawdust samples of these woods are related to their acid contents.

It had become evident in view of these observations that corrosion was due to acids derived from the conduit and therefore, from a knowledge of wood chemistry, principally acetic acid. Hence, the mechanism of the corrosion is the same as that involved in the production of "white lead." This reaction, from the classical point of view, consists in the formation of lead acetate, by the action of acetic acid and oxygen on lead, and the conversion of this product into a basic lead carbonate with the liberation of acetic acid which then repeats the process cyclically. Essentially the process is dependent upon the maintenance of a suitably high concentration of hydrogen ions and the presence of oxygen and carbon dioxide.

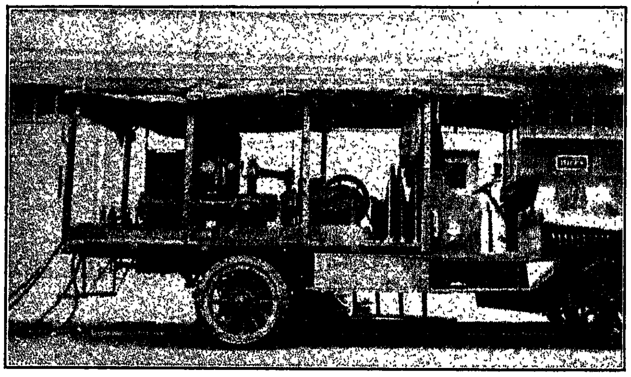

FIG. 2—APPARATUS FOR SUPPLYING AMMONIA TO NEUTRALIZE CREOSOTED WOOD DUCT

The determination of the cause of corrosion was, in one sense only preliminary to the important problem of finding a means of saving the cables which were in the process of corroding and to devise a method of treatment which would destroy the corrosiveness of idle ducts prior to their occupancy by cables. In this study comprehensive tests were carried on both in the field and in the laboratory. A large number of materials, including petrolatum, greases, oils, soap solution, water glass, pyridine, ammonium carbonate, ammonium dichromate, ammonia gas, etc., were tried out. Heavy petrolatum applied to cables upon installation gave some promise, but examination of the coated cables later revealed marked evidences of corrosion in areas where the grease had been rubbed off during the installation of the cable. Eventually the most effective palliative treatment was found to be ammonia gas which neutralizes the acetic acid forming ammonium acetate, a non-volatile salt.

A suitable apparatus was developed for supplying ammonia mixed with air to cable ducts.[4] This equipment consisted of a large capacity blower operated by a gasoline engine, a mixing tank, the necessary connections, and an outlet through a manifold for distributing the air mixture to the ducts. A tank of liquid ammonia was connected to the mixing tank through a flow meter. The system was mounted on a truck, as is shown in Fig. 2. The air-ammonia mixture found most suitable contained about 2 per cent ammonia, and this was used. The greater part of the affected creosoted wood conduit in the plant has now been given the ammonia treatment with the result that trouble due to corrosion has practically ceased. There is still some question as to the necessity of repeating the treatment, but the evidence indicates that a single application will suffice in perhaps all but the most severely corrosive ducts.

The final phase of the problem, not yet completed, has had to do with the determination of the source and process of formation of the corrosive acid in creosoted wood ducts. An extensive laboratory investigation has shown that Douglas fir is markedly more acidic than pine, which is used for conduit in other sections of the country, and that the acid content is increased by raising the temperature or increasing the duration of heat treatment. Douglas fir is particularly difficult to penetrate with creosote and the relatively longer duration of treatment which has been employed in an attempt to improve penetration has tended probably to increase the acid content of the product. There is evidence that the acid is associated with the untreated part of the duct and that the creosoted portion of the wood is not corrosive to cable sheath.

Discussion

D. W. Proebstel: An interesting case of lead-sheath corrosion occurred in Portland a few years ago in a section where waste slab wood and sawdust had formerly been dumped. This wood had later been covered with gravel. It was found necessary to install temporarily some 11-kv. cables in this section and these were laid in a fir-wood box which was buried in the sand. After they had been in operation a short while, we observed that the cable sheaths were badly corroded on the sides and top. The corrosion pits in some cases were so deep that they were practically through the sheath. The crystals on that sheath were white, what we would ordinarily call white lead.

We began to look for the reason for the phenomenon. Knowing the history, we concluded that fermentation of the old wood caused acetic acid gases to pass up through the cable and coming in contact with moisture condensation on the cable this started the chemical reactions that produced the corrosion.

There is a description of this case in the proceedings of the March 1927 meeting of the Northwestern Electric Light and Power Association Technical Session.

G. D'Eu Stachio: It is well known that the acid contents of wood vary with the age of the trees, the season of cutting, and the nature of the soil in which the trees are grown. As only some of the conduits mentioned in the paper gave trouble (corrosive effect), it seems possible that investigation of the above mentioned variable may show the cause for the irregularity of the trouble and means of prevention by selection of the wood.

Our experience is that concentration of 0.1 mg. of acetic acid per cu. ft. of air is practically not active on lead in the absence of moisture but quite active in moist air. The condensation of moisture in the conduit increases the concentration of acid in the condensed water which accounts for the corrosion occurring at the upper part or on the sides of the cable sheath where the drops of water are formed, and never at the bottom of the cables or in cables submerged in water.

Referring to the air-ammonia treatment, it seems that the treatment may need to be repeated at intervals as the authors point out that the wood is quite difficult to penetrate and that the acid is contained in the untreated inner parts of the wood. Thus much of the acid can hardly be reached by air-ammonia treatment, and may later be leached out and again cause trouble.

E. R. Northmore: We had several cable failures in an old duct line located in an alley and could find no effects of electrolysis, but the cables had the same appearance and were damaged similarly to the ones described by the authors of this paper. We found that this alley had been used by a large number of truck horses for years and the fiber ducts had absorbed moisture. This had formed acetic acid and the lead was attacked as in the old Dutch process used in making white lead.

I should like to ask the author if he had ever experienced similar trouble with fiber ducts; while we have had no trouble of this character with fiber ducts installed in the last few years, our trouble was all in ducts 25 to 30 years old.

Also, how often will it be necessary to use this ammonia treatment?

J. H. Johnson: I should like to ask the author if he made tests for electrolysis, or tests on the local current form, because besides the flow of current from outside sources, there may be concentration due to the chemicals adjacent to the lead. The forces may be generated through difference in temperature. So I am wondering if any tests were made to see if there were local currents in that sheath caused by difference in conditions.

R. M. Burns and B. A. Freed: The case of corrosion described by Mr. Proebstel is of considerable interest and was due, we believe, to acetic acid originally present in the raw fir wood and did not depend necessarily upon a fermentation process.

Referring to Mr. D'Eu Stachio's discussion we may say that we have observed a variation in the acid content of wood samples from different trees of both fir and hemlock, but the magnitude of this variation for a given species is not sufficient, in our opinion, to furnish a basis for the selection of non-corrosive specimens. As to the effectiveness of the ammonia treatment, it has been found that a second treatment is necessary in a small per cent of the cases where the acid content was exceptionally high. We do not believe that neutralization of the acid is accomplished by ammonia penetrating the wood, but rather by absorption of the acid vapors by the ammonia solution. The moisture in the duct and on the cable is converted into an ammonia solution at the time of the ammonia treatment and tests have shown that ammonia persists in the ducts in some cases for more than five months. In other words, treatment with ammonia neutralizes the readily accessible acid in the duct and on the cable and forms an ammonia solution which then absorbs acid vapors which may come from the wood during a period of several months. The acid remaining in the wood after that period does not appear to furnish dangerous concentrations of acid vapor to the duct air.

Replying to Mr. Northmore's inquiry, we may say that our field inspection did not disclose any cases of corrosion in fiber conduit, though reports have been received that traces of corrosion have been found in fiber duct placed in early years.

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[4] This apparatus was devised by E. M. Honan and E. G. D. Paterson of the Bell Telephone Laboratories and will be the subject of a separate paper.

System Stability as a Design Problem

BY R. H. PARK* and E. H. BANCKER*
Associate, A. I. E. E. Associate, A. I. E. E.

Synopsis.—*Under modern conditions of operation the ability of the component machines of a power system to hold in step during system disturbances has become of major importance in the choice of system layout and machine design. This situation has greatly stimulated activity in the study of the problems involved. This paper reviews the general problem in the light of recent analytical and experimental studies made by the authors. The subject matter of the paper is grouped according to the following headings:*

Part I reviews the factors affecting stability, including generator short-circuit ratio, voltage regulators, excitation systems, neutral impedance, governors, amortisseurs, intermediate condensers.

Part II gives methods of calculating stability, under the following heads: preliminary calculations, idealized case of two machines, general case of two machines, extension to include more than two machines, simplified method of calculating tie lines.

The appendixes include an example illustrating the method of calculation in a particular case.

* * * * *

ORIGINALLY the maximum power output of synchronous apparatus was fixed by the maximum current which the machines could supply without excessive heating, while the maximum power which could be transmitted economically over a transmission line was determined by the allowable losses in the line.

However, as progress was made in the design of electrical machinery and as the voltages at which power was transmitted were increased, it was found that the line and machine reactances must be held low enough to avoid the possibility of pull-out or instability, whether occasioned simply by excessive loads or by system disturbances.

Practically this situation was met principally by designing generators with high enough short-circuit ratio, and lines with low enough reactance to meet ordinary requirements. At the same time, however, the latent economic advantages in view have greatly stimulated interest in the development of means auxiliary to these, by which increases in stability of operation can be economically effected.

Further, there has been an active demand for more accurate methods of calculating stability, in order to make possible the design of systems on a rational basis. The present paper presents first, a brief review of the principal factors affecting the stability of power systems; and second, a summary of some of the methods of calculation which the authors have employed in the study of practical systems.

Part I

REVIEW OF FACTORS AFFECTING STABILITY

a. Generator Short-circuit Ratio. In general the maximum power that can be delivered by a synchronous generator depends upon the character of the load circuit to which the generator is connected. To illustrate, suppose that a turbo alternator is supplying power for an induction motor load connected directly to its terminals, and suppose that as the induction motor load is gradually increased the generator terminal voltage is maintained substantially constant by occasional manual adjustment of the generator's exciter field rheostat. Further, suppose in the interests of simplicity and definiteness that it is provisionally agreed that the effects of saturation may be neglected in both machines. In this case, neglecting armature resistance the system may be represented by the equivalent electrical circuit of Fig. 1.

where e = generator terminal voltage
E = generator nominal voltage
R = induction motor rotor resistance
x_m = induction motor magnetizing reactance
x_s = generator synchronous reactance
x = induction motor rotor reactance
s = induction motor slip

from which the relation of slip and mechanical torque may be found.

In general the mechanical load of the motor will depend upon its slip, but for any given speed-torque characteristic of the shaft load, there will be some definite value of load, slip, and excitation. If the generator excitation is held constant while the slip is increased due to a momentary increase in the motor load torque, the system will be stable and will return to a position of equilibrium, if $\frac{dT}{ds} > \frac{dL}{ds}$, where L = induction motor

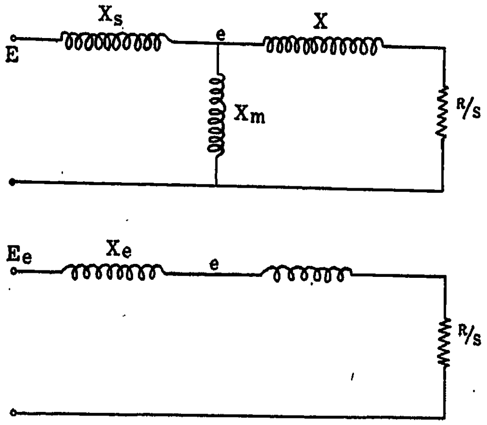

FIG. 1—EQUIVALENT CIRCUIT OF SYNCHRONOUS GENERATOR SUPPLYING AN INDUCTION MOTOR LOAD

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*Both of General Electric Co., Schenectady, N. Y.

Presented at the Pacific Coast Convention of the A. I. E. E., Spokane, Wash., August 28-31, 1928.

load torque; T = torque exerted by induction motor.

Thus, Point A, Fig. 2, shows a condition of stable operation and Point B one of unstable operation.

Actually the motor load will depend upon the motor speed rather than merely upon its slip with respect to the generator. As the generator has a load-speed characteristic of its own it would be necessary in general to give consideration to it. If the induction motor is supplying a constant torque load, instability will occur with $\frac{d\,T}{d\,s} = 0$. For equal machines, choosing $x = 0.15$, $x_m = 3$ in per unit* of machine reactance, the torque at instability is found to vary in this case with generator per unit reactance, as shown in curve A, Fig. 3.

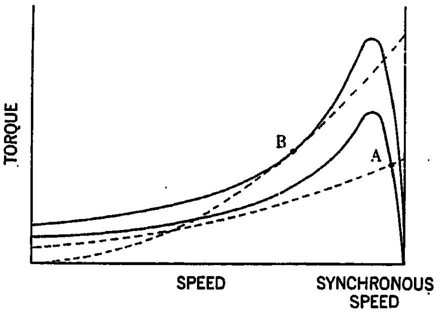

Fig. 2—Torque Speed Curves of Induction Motor and Load

——— Motor characteristic
– – – Load characteristic

On the other hand if the load torque is proportional to the square of the speed—*i. e.*, to $(1 - s)^2$, as would occur substantially with a fan or centrifugal pump load, it is impossible to find any condition under which $\frac{\alpha\,T}{d\,s} < \frac{d\,L}{d\,s}$, *i. e.*, the motor cannot be unstable. However, there is a maximum torque which can be carried in this case. This is shown in Curve B of Fig. 3.

It will be seen that in general the generator synchronous reactance must not exceed approximately 1.20 for stability at full-load. In practise the effects of saturation and of any shunt load will be to permit a higher value of machine reactance with stability.

Were the induction motor replaced by a synchronous motor there would be with equal excitation and neglecting salient poles,

$$T = \frac{E^2 \sin \theta}{2\,x_0}$$

where θ = displacement angle of machine rotors.

Instability occurs at $\frac{d\,T}{d\,\theta} = 0$, *i. e.*, at $\theta = 90$ deg. for which $E = \sqrt{2}\,e$, so that with normal terminal voltage ($e = 1.0$)

$$T_{max.} = \frac{1}{x_0}$$

Thus, in this case the generator and motor per unit synchronous reactances must not exceed unity for stability at full load, while if the generator and motor are separated by a transmission line it is necessary that their reactances be less than unity for stability under the same conditions. Actually, of course, as mentioned in the previous instance, the effects of saturation and of impedance load are to reduce the requirements as to low synchronous reactance, or what is substantially the same thing, high short-circuit ratio. Nevertheless, even considering this circumstance the fact remains that machines which are to be operated with manual control of excitation require in general a short-circuit ratio in the neighborhood of unity,† especially if ability to operate through severe system disturbances is desired, while if long distance transmission over high-voltage lines is involved a short-circuit ratio considerably higher than unity may be found advantageous.

When synchronous machines were first being built this limitation was not felt, since the requirements for inherent voltage regulation necessitated construction with high short-circuit ratio. The advent of the Tirrill regulator largely disposed of this necessity. This circumstance, together with the development of improved designs permitting greater current loading of the armature, has established a considerable inducement toward the use of machines of low ratio both from the standpoint of reduction in first cost and improvement in efficiency. On the other hand power transmission developments have tended to demand a high ratio.

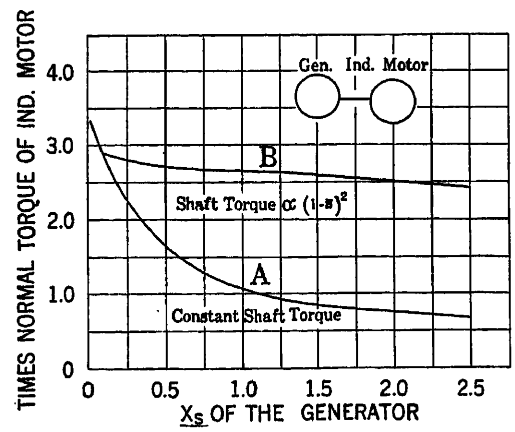

Fig. 3—Calculated Values of Maximum and Critical Torque of Induction Motor Connected to a Synchronous Generator, as a Function of Generator, Synchronous Reactance, (X_S)

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*Fraction of normal: Thus 3 per unit = 300 per cent; reference (5).

†Bibliography 11.

b. Voltage Regulators. If the excitation voltage can be continuously varied in proper phase relation to the machine terminal voltage it is possible to operate above the limit of stability with hand control. Recent tests have shown that when an appropriate type of regulator is employed a large gain in stability is available both under steady and transient conditions. Thus, Fig. 4 shows the gain in steady-state stability due to such a regulator as a function of the length of the transmission circuit. In the case of system disturbances the regulator has an additional function to perform; *viz.*, to rapidly effect a substantial increase in the exciter voltage, thus reducing the decrease of field flux linkages which would otherwise occur, or actually causing them to increase. In practise the gain to be anticipated in stability through faults depends both upon its ability to effect rapid increases in excitation and upon its ability to resume "balancing" after the initial phase of the disturbance is past.

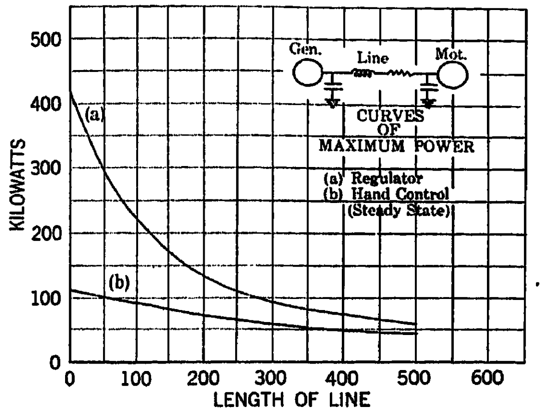

FIG. 4—TEST DATA

Steady load which can be carried over model line. (exciter speed less than 250 volts/sec.)

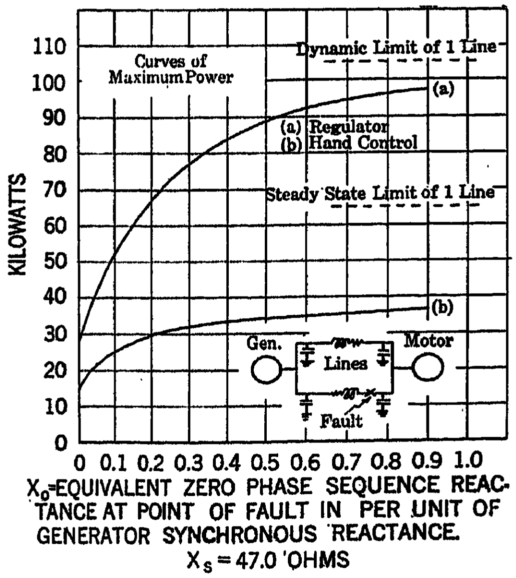

FIG. 5—TEST DATA

Power which can be carried through a line to ground fault on one of two parallel 250-mi. model lines. Fault cleared at both ends of line in 0.6 sec. Fault on generator bus corresponds approximately to $X_0 = 0.10$; fault at other points of the line corresponds to $X_0 > .1$

(Exciter build-up speed of 225-250 volts per sec.; exciter ceiling 320 volts; exciter operating voltage 70 volts)

The magnitude of the gain to be anticipated in practise is illustrated by Figs. 4 and 5.

Besides its effect in increasing the stability of machines of normal design the regulator should make possible the utilization of machines of lower short-circuit ratio than would otherwise be practicable for by its action it provides the stability that could not otherwise be obtained in machines of this type.

The regulator has a further field. It may also be applied with benefit to synchronous motors and frequency converters, especially when severe load surges are to be encountered. The gain to be anticipated should be especially great with this class of apparatus since it operates substantially from an infinite bus; *i. e.*, there is no transmission line.

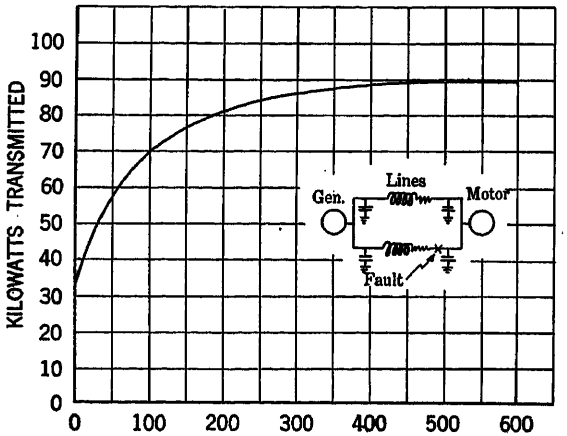

FIG. 6—TEST DATA

Showing the effect of speed of excitation on the transient stability of the model transmission system (ceiling voltage 320 volts; operating voltage 70 volts)

c. Excitation Systems. The gains in stability which can be effected by a voltage regulator of a given type depend upon the rate of voltage build-up of the exciter, and upon its operating and ceiling voltages.

The available data indicates that if normal ceiling voltage is available, a moderate speed of excitation, say for large machines 150 to 200 volts per sec.,* is sufficient in the usual case to prevent pulling out of step on other than the first swing of the machine rotors. In general the gain due to a higher speed of build-up than this is small in comparison with the gain obtainable with the speed of excitation referred to, since with these higher speeds the time available for modifying the rotor flux linkages is small (of the order of ¾ sec.). Thus careful step-by-step calculations were made in the case of three representative systems in which water-wheel generators feed load centers over transmission lines of respectively 60, 120, and 250 mi. The results showed that the power which can be carried without pull-out on the first swing of the machine rotors, after the occurrence of a line to ground fault on the generator bus, is only from four to six per cent more with excitation sufficient to maintain constant rotor linkages* than can be so carried with a speed of excitation sufficient to prevent pull-out on the second swing, *i. e.*, about 150 to 200 volts per sec.* This conclusion is borne out by the test data in Fig. 6 which shows the gain in transient stability as a function of exciter speed for a line to ground fault on one of two 250-mi. lines.

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*For 250-volt fields. One-half as much for 125-volt fields.

As these data were taken with small machines the excitation speeds shown should be multiplied by a factor less than unity in order to pro-rate them to correspondence with large machines. This factor probably ranges from 0.5 to 0.6.

On the other hand, in some cases, and especially in connection with synchronous condenser stations, it may be desirable to secure additional stabilizing action by building up the machine excitations to a very high value within a fraction of a second. To achieve this result requires a new type of exciter; one with a high ceiling voltage, and with a correspondingly high speed of build-up.

d. Neutral Impedance. The generally admitted circumstance that the majority of transmission line lightning flashovers establish arcs from one line to ground, and thus that this type of fault is of primary importance in determining the transient stability of transmission systems, suggests the desirability of using current limiting resistors or reactors in the high-voltage transformer neutrals, or as an equivalent grounding the neutral, and designing the transformer for high impedance to ground current.

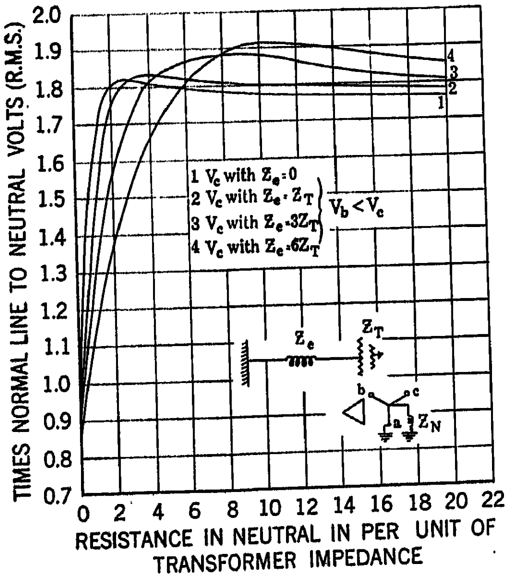

FIG. 7—CALCULATED LINE TO GROUND VOLTAGES ON THE OPEN PHASES WITH A LINE TO GROUND FAULT, AS A FUNCTION OF RESISTANCE IN THE NEUTRAL

Obviously any means for reducing the magnitude of the system fault current is beneficial from a stability standpoint. In general, however, it is desirable that enough reactive current be permitted to flow to allow rapid selective relaying by ground current relays, and to avoid the possibility of arcing grounds. Consideration is invited to the greater use of reactors instead of the usual resistors. In principle, a reactor in the neutral is no more likely to cause excessive system voltages than a grounding transformer is, that is, precautions against excessive voltages are not necessary unless the reactor approaches the dimensions of a Petersen coil. Also even with a Petersen coil there does not appear any source of danger which cannot be overcome with relative simplicity. In most cases, however, very large gains in stability are obtainable with reactors which do not even approach to the Petersen coil value, *i. e.*, to a value such that the reactor current equals the fault charging current.

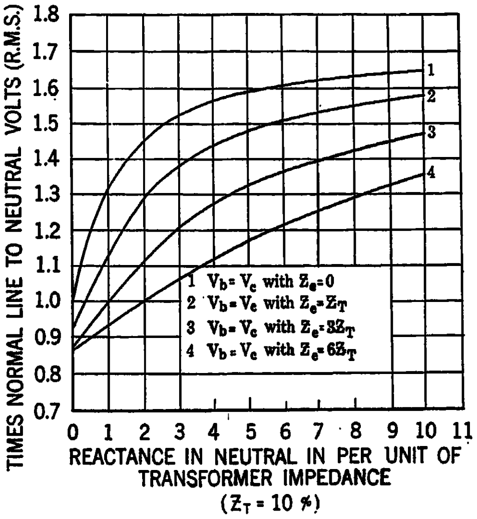

FIG. 8—CALCULATED LINE TO GROUND VOLTAGES ON THE OPEN PHASES WITH A LINE TO GROUND FAULT, AS A FUNCTION OF REACTANCE IN THE NEUTRAL

The principal advantage of reactors as compared with resistors are their greater reliability, usually lower cost, and the fact that in case of line to ground fault they tend to increase the phase to ground voltage on the clear phases to a much lower extent. This last factor which is illustrated in Figs. 7 and 8 is of great importance in connection with duty on lightning arresters. In order to obtain an appreciable gain in stability the resistance must be considerably greater than the system reactance viewed from the point of fault. Referring to figure this means that the voltages to be anticipated from a clear phase to ground are necessarily $\sqrt{3}$ or more times normal voltage.

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*Equivalent to about 600 volts per sec. with a normal ceiling exciter.

With a reactor this is not the case, and in fact a marked gain in stability can be obtained with a value of reactance such that clear phase to ground voltage is say less than 30 per cent more than normal.

Although the use of grounding reactors of high enough reactance to approach the Petersen coil value has not been recommended generally, it is felt that in a large number of cases the use of Petersen coils may nevertheless be desirable, provided that suitable precautions are taken to prevent the occurrence of excess voltages during switching.

In general, it is also desirable to check for the possibility of corona under fault conditions. The method of calculation is discussed in Appendix III.

e. Governors. In a considerable number of instances momentary system disturbances have been followed by prolonged hunting due to "pumping" of the steam turbine governors. This condition usually arises when the regulation of the governors, that is the speed range from no-load to full load with synchronizing spring fixed, is unduly low. To avoid hunting of this character it is desirable that the regulation be four per cent or above.

f. Amortisseurs. In general any damping influences in a system tend to improve stability, and especially in connection with systems involving a number of independent machines each of which is capable of swinging more or less independently of the others. Further, when high resistance lines are involved, stable operation of laminated pole machines without damping windings may be impossible under some load conditions. A consideration of these factors suggests the general desirability of equipping water-wheel generators with low resistance amortisseur windings.

g. Intermediate Condensers. The use of synchronous condensers or of synchronous condensers in combination with shunt reactors is sometimes preferable to the construction of additional overhead line. In such cases, however, it is probably desirable that use be made of a balancing type of voltage regulator, as the stabilizing influence of the condenser is greatly increased in this way. Thus, shop tests on a model 500-mi. line show the following results:

Gain in steady power limit over hand control value with no condenser

a. With regulator on generator and motor but no condenser 21 per cent,

b. With intermediate condenser equal in size to generator and motor but hand control on all machines 25 per cent,

c. With intermediate condenser and regulator on all machines 99 per cent.

When the regulator is used throughout, the gain affected by the condenser is $199 \div 121 - 100 = 64$ per cent. When hand control is employed, the gain due to the condenser is only 25 per cent.

While the effect of short circuits and other disturbances will, in general, be such as to reduce the power which can be carried with stability, the gain from an appropriate regulator will probably be about as under steady-load conditions.

In order to reduce to a minimum the adverse effect on stability of short circuits and similar disturbances, the use of a high ceiling or superexciter would appear to be, in general, desirable. The exciters for the condensers of the Plymouth Meeting Station of the Philadelphia Electric Company with a ceiling of 950 volts and an exciter speed of 6400 volts per sec. illustrates this principle. The calculated gain in stabilizing influence is such that three condensers with the exciter are found to be equivalent as regards transient stability to five with ordinary speeds of excitation.

Part II

METHODS OF CALCULATING STABILITY

Originally the stability of power systems was calculated principally in terms of the maximum power which could be carried under steady-load conditions. In general, knowledge of the steady power limit of a system is valuable, since it indicates the margin of stability available under normal conditions, and thus, when coupled with an experience factor, gives a measure of the power which can be carried through disturbances. However, a much more direct and accurate method of approach to the problem is to calculate the effect of disturbances directly, that is, to calculate stability under transient conditions.

Several valuable papers have been published in the past, dealing with this problem.* The present paper provides a review of the methods previously established and extends them to include any number of machines and the effect of salient poles. Also, simplified methods of calculations have been developed for application in special cases where their use is justified.

a. Preliminary Calculations. The first step in the treatment of any actual system is its simplification to an equivalent system which will substantially represent the real one, particularly as to reactance and flywheel effect. Often it is permissible to reduce a group of machines to a single machine unit, since the individual parts are coupled closely enough to be so treated. Thus, it is assumed that within such a group, though there may be local oscillations between the parts, the net effect is the same as the single unit. The process of simplification thus consists in the replacement of part of the system by a unit machine, either synchronous or induction, which behaves with respect to observations made on the connecting lines in substantially the same manner as it is expected that the part of the system would.

In order to select intelligently the equivalent machines, it is first necessary to choose substantially correct values of reactance for the units of the real system. The larger units such as generators, condensers, and possibly large synchronous motors may be correctly represented by their actual values if known. Attention is called to the fact that the value of transient reactance composed of stator and field leakage is to be used and not the subtransient which includes the effect of amortisseurs, etc. The latter has frequently been confused with transient reactance since it is used in determining the instantaneous current rush during a short circuit. The effects which cause it to differ from transient reactance, disappear so rapidly that in any study of conditions obtaining more than a few cycles after the occurrence of a transient, the real transient reactance should be used. It is most convenient to combine the smaller loads into substation loads. Thus each station would have one resistance load, one induction motor load, and one synchronous load, each equal to the total load of that particular character supplied from that particular station. Tables I to III show the average per unit reactances applying to the different classes of apparatus and the values given in it may be used for all apparatus whose actual values are unknown.

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*Bibliography 3, 12, 13.

These reactances are based on kilovolt-ampere rating so that when the load is known in kilowatts, allowance must be made for the difference. If data are available regarding the connected kilovolt-ampere of load per kilowatt, they should be utilized in making this correction, but if not, certain assumptions may be made which will give approximately correct results. The induction motor load is assumed to be composed of a number of 75 per cent loaded motors which would have 0.89 power factor at full load and enough unloaded motors to bring the total power factor down to 0.7. From these premises it may be shown that the kilovolt-ampere rating of the induction motor load is 2.75 times the kilowatt load. The synchronous motors are assumed at half load and their rating in kilovolt-ampere is accordingly 2 times kw. at rated power factor.

Having assigned reactance to all of the apparatus, the positive, negative, and zero-phase sequence reactances of the receiver system viewed from the point of interconnection are found in the usual manner, either by computation or from the d-c. calculating table. The current in any circuit is obtained from the loads and terminal voltages. When the currents are known the machine field flux linkages and excitation may be found from the m. m. f. diagram. Fig. 9 shows the most general form of such a diagram. The figure is adapted from that shown in the paper *Synchronous Machines II* by Messrs. Doherty and Nickle, by introducing terminal linkages and rotor excitation, and discarding nominal voltages. Rotor linkages and the linkages inside transient reactance are also shown. The latter is represented physically by the initial terminal voltages which would be obtained if the armature were suddenly open circuited. It is desirable to work with linkages instead of voltage due to the fact that the machine torque can be expressed in terms of linkages and displacement angle, while if voltages are used the speed must be considered.

To represent the real system, the replacing machines should have the same inertia effect as the groups which they represent. This is readily found as the sum of the inertia constants of all the rotating apparatus in the group. Where the $W R^2$ of a machine is known, the inertia constant M may be calculated from the equation

$$M^* = \frac{0.462\, W R^2 \left[\frac{\text{r. p. m.}}{1000}\right]^2}{\text{Base kw.}} \text{ (sec).}$$

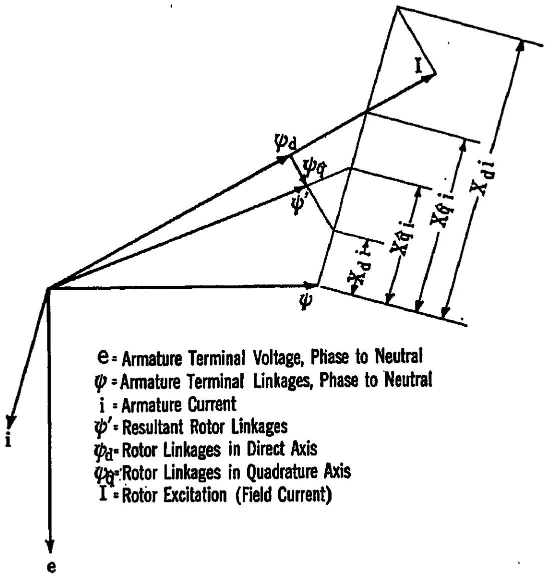
I
ψd
ψq
ψ'
ψ
Xd'i
Xqi
Xq'i
Xdi
i
e
e = Armature Terminal Voltage, Phase to Neutral
ψ = Armature Terminal Linkages, Phase to Neutral
i = Armature Current
ψ' = Resultant Rotor Linkages
ψd = Rotor Linkages in Direct Axis
ψq = Rotor Linkages in Quadrature Axis
I = Rotor Excitation (Field Current)

FIG. 9—GENERAL MAGNETOMOTIVE FORCE DIAGRAM

For those machines whose inertia is not known, representative values may be obtained from Table IV. Before adding the inertia constants, they must be calculated to a common kilowatt base and therefore the values given in the table are multiplied by the ratio of kilovolt-ampere rating to kilowatt base. In general it is preferable to use the same kilowatt base as the kilovolt-ampere base on which the reactances are calculated so that both kilowatt and kilovolt-ampere are expressed as per unit values of the same number.

TABLE I

SYNCHRONOUS REACTANCES

	In direct axis	In quadrature axis
Turbo alternators	110 per cent	110 per cent
Synchronous motors	100 per cent	60 per cent
Synchronous condensers	150 per cent	85 per cent
Water-wheel generators	100 per cent	65 per cent
Induction motors	300 per cent	

TABLE II

TRANSIENT REACTANCES

	In direct axis	In quadrature axis
Turbo alternators	18 per cent	18 per cent
Synchronous motors	30 per cent	60 per cent
Synchronous condensers	40 per cent	85 per cent
Water-wheel generators	30 per cent	65 per cent
Induction motors	15 per cent	

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*M = 2 times stored energy divided by base power.

TABLE III

NEGATIVE PHASE SEQUENCE REACTANCES

Turbo alternators	14 per cent
Synchronous motors	22 per cent
Synchronous condensers	28 per cent
Water-wheel generators	40 per cent
Induction motors	15 per cent

TABLE IV

INERTIA AND OPEN CIRCUIT TIME CONSTANTS

	M = inertia constant	T_0 = open-cir. time constant
Turbo alternators	16.0	5—8
Synchronous motors	4.5	2—4
Synchronous condensers	3.0	5—7
Water-wheel generators	6.0	4—6
Induction motors	1.0	

TABLE V

ZERO-PHASE REACTANCE OF LINES†

1. Three-conductor line
    - (a) Heavy non-magnetic ground wire use 2 x pos. seq. reactance
    - (b) Light steel ground wire use 3½ x pos. seq. reactance
    - (c) No ground wire use 3½ x pos. seq. reactance
2. Three-conductor lines
    - (a) Heavy non-magnetic ground wire use 3 x pos. seq. reactance
    - (b) Light steel ground wire use* 5 x pos. seq. reactance

*This value used in example in Part II.

†When more accurate figures are desired they may be calculated by the method given in Appendix II.

b. Idealized Case of Two Machines. It is sometimes sufficiently accurate to regard a generator feeding a system as equivalent to a simple system comprising a line connecting two round rotor machines, with negligible resistance and damping. For example, a generator supplying a system through a line may be reduced to the simple system shown in Fig. 10.

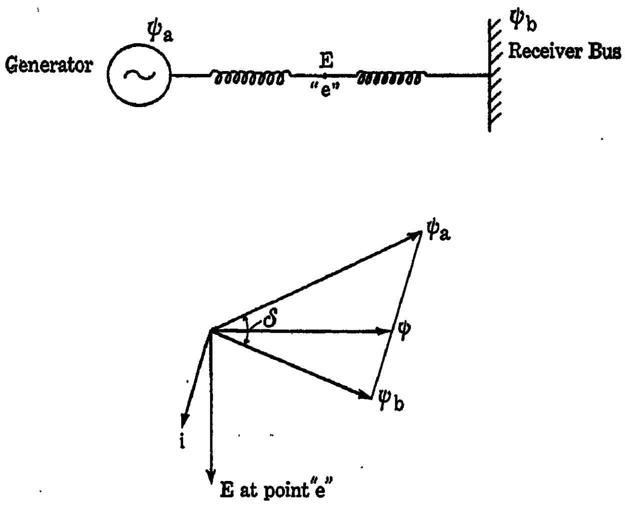

Fig. 10—Simplified Equivalent of Generator Supplying a System through a Line with Vector Diagram of Current, Voltage, and Linkages

Further, if only the first swing is under consideration, or if more than the first swing is to be considered but a suitable regulator and exciter are available, on the basis of these premises it is approximately correct to assume that the machine field circuit flux linkages remain constant. The initial conditions are determined from a vector diagram as shown in Fig. 10.

The power transfer at any angle is $T = \frac{\psi_a \psi_b}{x} \sin \delta$ where ψ_a and ψ_b are the flux linkages of the equivalent machines, x is the total transient reactance between the linkages, and δ the angle between the rotors. The maximum power occurs at $\delta = 90$ deg. and is $T_m = \frac{\psi_a \psi_b}{x}$. Fig. 11 shows the power angle or, more strictly, torque angle characteristic.

Consider then a system having the characteristic shown in Fig. 11, and operating at an initial angle δ_0 corresponding to a torque T_0 and suddenly impress a mechanical torque T_1 upon the motor. The acceleration at any time is proportional to $T_1 - \frac{\psi_a \psi_b}{x} \sin \delta$ and the work done upon the rotor in giving it a velocity is equal to the integral of this quantity with respect to δ, which is the area between T_1 and the torque angle curve. By the time the angle has increased to δ_1 the rotor has acquired a velocity proportional to the work done upon it and will therefore overtravel until it gives up as much work as it received, or until the area above T_1 equals that below.† If too high a torque is impressed, the area above can never equal that below. The rotor swings until the electrical torque is less than the mechanical torque and the machine falls out of step.

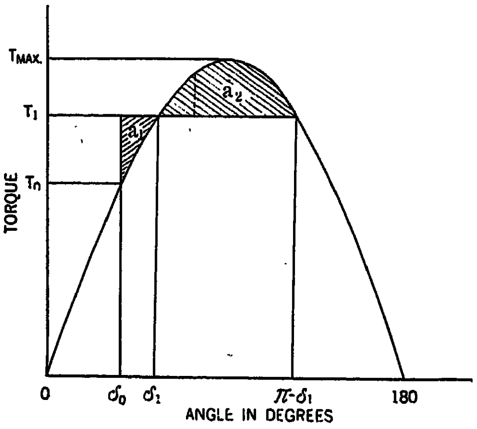

Fig. 11—Torque Angle Diagram showing Effect of Suddenly Applied Load

There is then a maximum that may be so applied without loss of synchronism, this maximum varying with the previous steady load T_0. The curve in Fig. 12 shows the maximum additional load which may be thrown on with stability maintained as a function of initial load, all values being expressed in per unit of the maximum steady-state power. In using this curve, it should be remembered that it holds true only when one machine has infinite inertia. In the case of two finite inertia machines with sudden application of torque to one end only, and a gradual rise in torque at the other, as the speed drops, the maximum is higher than is shown on the curve and is dependent upon the rate of rise of torque and the relative inertias.

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†See Bibliography 12, 15 and 19.

When one of a number of parallel circuits is opened, the circuit reactance is increased and the maximum steady-state power reduced. Thus, if the torque angle characteristic of a circuit with two lines in service is given by curve A in Fig. 13, and one line is suddenly opened, it becomes curve* B. If the system has an initial load of T_0 and is at an angle δ_0 the torque will immediately change to T_1. The effect is the same as though the system had been operating with curve B characteristic and an initial load T_1, and the mechanical load, were suddenly increased at both ends to T_0. Applying the reasoning outlined above regarding a suddenly applied load and the work area, a curve such as Fig. 14 may be plotted showing the maximum load that may safely be carried if a circuit is to be opened.

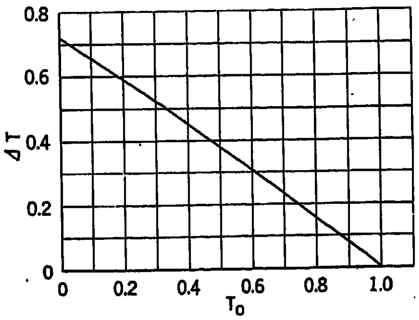

Fig. 12—Transmission Line Connecting Two Zero Reactance Machines

Effect of a suddenly applied load
T_0 = Intial torque
ΔT = Maximum sudden increase in torque with stability maintained
Maximum sudden increase in load with stability as a function of initial load

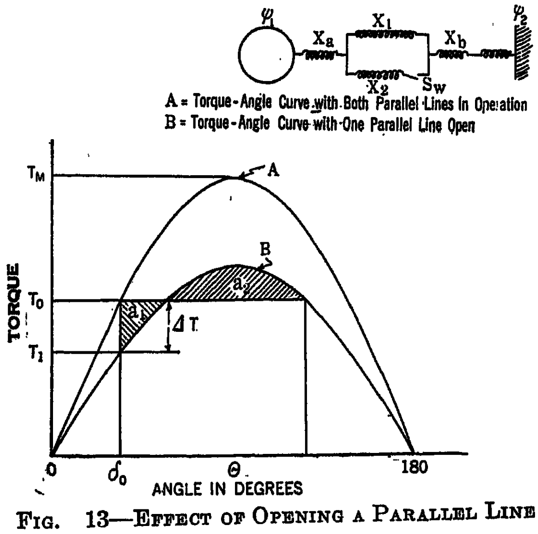
ψa
Xa
X1
Xb
ψb
X2
Sw
A = Torque-Angle Curve with Both Parallel Lines in Operation
B = Torque-Angle Curve with One Parallel Line Open
TM
A
B
a2
a1
ΔT
TORQUE
T0
T1
0
δ0
θ
180
ANGLE IN DEGREES

Fig. 13—Effect of Opening a Parallel Line

When a change in torque occurs, the rotors of the machines must move to new angular positions and they will accelerate in proportion to the net torque acting upon them and inversely as their inertias. The total angle between two machines having inertia constants M_1 and M_2 is the same at any instant as the angle between two machines having constants infinity and $M = \frac{M_1 M_2}{M_1 + M_2}$ respectively. On this basis

$$t = \sqrt{\frac{M x}{4 \pi f \psi_a \cdot \psi_b}}\, F\,(\delta, T_1/T_m, T_0/T_m)$$

where t = time in seconds
f = frequency

$F\left(\delta, \frac{T_1}{T_m}, \frac{T_0}{T_m}\right)$ is shown in Figs. 15, 16, 17, and 18.

In its action upon the positive phase sequence network, a short circuit is the same as connecting a three-phase shunt reactor at the point of fault.† If the short circuit is three-phase, the reactance of the shunt is zero. If line to line, it is the total negative phase sequence reactance of the system as viewed from the point of fault, and if line to neutral, it is the sum of the negative and zero-phase sequence reactances to the fault.

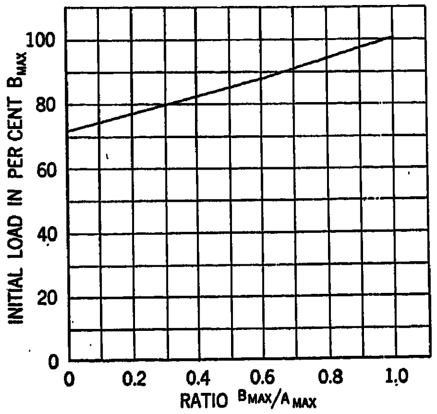

Fig. 14—Maximum Initial Load with Stability on Opening a Parallel Line

Under the assumed conditions of negligible resistance and no damping, there is neither any negative nor zero-phase sequence power and it is merely necessary to calculate the positive phase sequence power. The positive phase sequence diagram for the system shown in Fig. 10 becomes as shown in Fig. 19, for a line to neutral short circuit. An equivalent reactance may be obtained by paralleling the shunt with the reactance of the system from that end to the point of fault and changing the flux linkages of the machine with which it was combined to $\frac{x_0 + x_2}{x_0 + x_2 + x_b}$ times its former value. If it is combined with the receiver, the system becomes as shown in Fig. 19.

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*See Appendix VI.

†See Appendix (VII).

The torque angle characteristic is then

$$T = \frac{\psi_a \, \psi_b}{x_a + x_b + \dfrac{x_a \, x_b}{x_0 + x_2}} \sin \delta$$

where x_a = positive phase sequence reactance from generator to point of fault.

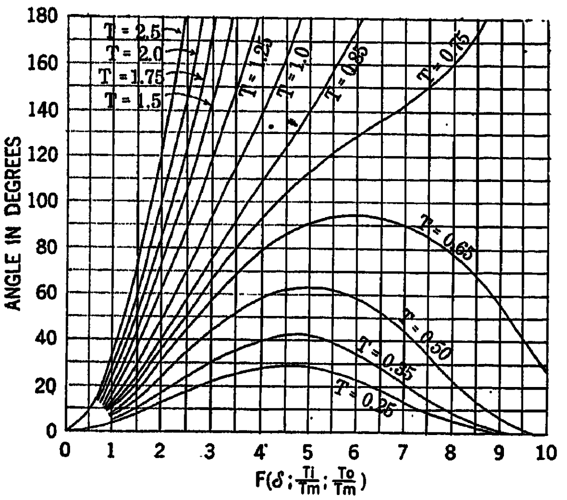

FIG. 15—ANGLE TIME CURVES FOR SEVERAL VALUES OF $T = \frac{T_1}{T_m}$, T_0 = 0.0 OF TOTAL TORQUE

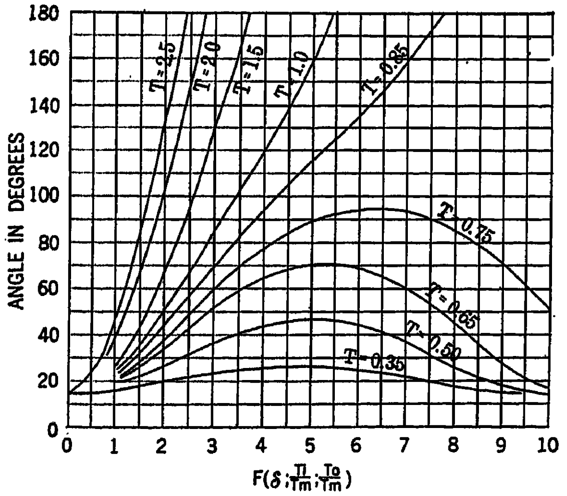

FIG. 16—ANGLE TIME CURVES FOR SEVERAL VALUES OF $T = \frac{T_1}{T_m}$, T_0 = 0.25 OF TOTAL TORQUE

x_b = positive phase sequence reactance from receiver to point of fault.

x_2 = total negative phase sequence reactance of system to point of fault.

x_0 = total zero-phase sequence reactance of system to point of fault

This characteristic is shown as the curve *B* in Fig. 20 Curve *A* is that obtaining prior to the short circuit.

Let the initial load and angle be T_0 and δ_0. At the instant of short circuit, the angle would remain unchanged and the electrical load would drop to T_1, the shaft torques, however, remaining constant at T_0. Again the effect is the same as though the system had been operating on the lower characteristic at a load T_1 and that the shaft torques had suddenly been raised to T_0 and the treatment is, therefore, identical with that given previously for a suddenly applied load. Insertion of the proper constants in the term to convert $F\left(\delta, \frac{T_1}{T_m}, \frac{T_0}{T_m}\right)$ seconds enables the rotor angle displacement to be found at any time t.

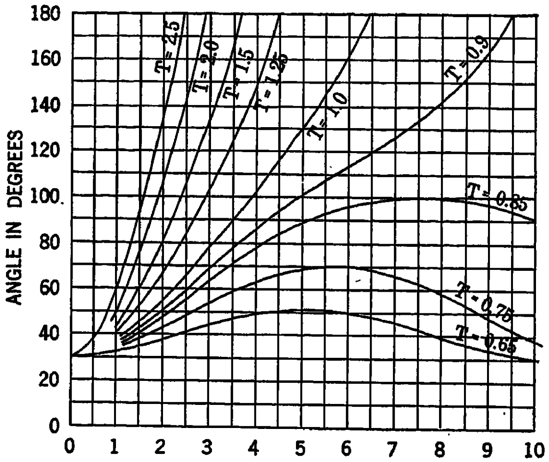

FIG. 17—ANGLE TIME CURVES FOR SEVERAL VALUES OF $T = \frac{T_1}{T_m}$, T_0 = 0.50 OF TOTAL TORQUE

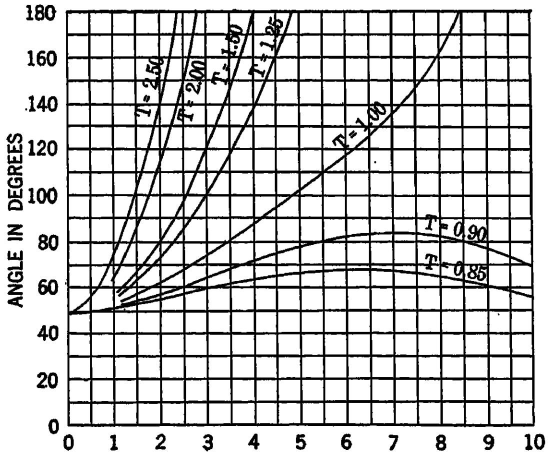

FIG. 18—ANGLE TIME CURVES FOR SEVERAL VALUES OF $T = \frac{T_1}{T_m}$, T_0 = 0.75 OF TOTAL TORQUE

The purpose in finding the angle is to determine the behavior following the clearing of the short circuit and the angle should, therefore, be found at the time at which it is expected the circuit breaker will interrupt the fault current.

If the fault has been on a feeder, the opening of the circuit breaker does not change the system reactance and the circuit again returns to its original condition and torque angle characteristic. During the period of the short circuit, the rotors acquired a velocity and a new angle. Referring again to Fig. 20, the energy which has been imparted to the rotors during the fault time is represented by the shaded area a_1. At the angle δ_1, the short circuit was cleared and the electrical torque immediately rose from x to y. The rotors will continue to swing until the shaded area a_2 is equal to a_1, or in other words, until the stored energy has been given up. If the area a_2 does not equal a_1, it indicates that at an angle $\pi - \delta_0$, which is the maximum to which the rotors may separate and still transmit the required power, the rotors still have a velocity apart and will fall out of step. The criterion of stability is, therefore, the relative size of areas a_1 and a_2, or of the rectangle $\delta\, e\, f\, g$ and the area enclosed within the heavy line. The area of the rectangle is $T_0\,(\pi - 2\,\delta_0)$.

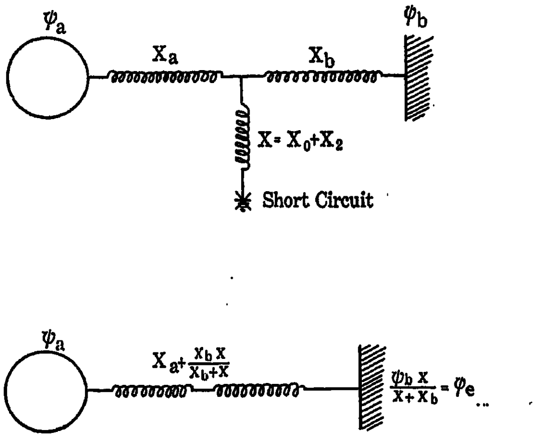
ψ_a
X_a
X_b
ψ_b
$X = X_0 + X_2$
Short Circuit
ψ_a
$X_a + \frac{X_b X}{X_b + X}$
$\frac{\psi_b X}{X + X_b} = \psi_e$

Fig. 19—Method of Treating a Line to Ground Fault

The area of the irregular curve is $= T_m\,\{(1 + r_1)\cos\delta_0 + (1 - r_1)\cos\delta_1\}$.

δ_1 = angle at which circuit breaker opened.

r_1 = ratio of the peak of torque angle curve with short circuit on, to the peak of the initial curve.

If the area of the rectangle is larger than that of the irregular curve, the system will be unstable.

When a short circuit takes place on one of the interconnecting lines of the system, its isolation causes a return not to the original condition, but to some third one. Assume a short circuit to have occurred at the receiver end of one of the tie lines of Fig. 13 and that it has been cleared. Up to the time of the opening of the breaker there is no difference between such a fault and one on a feeder off the receiver bus, but following its disconnection, the torque angle characteristic is given by $T = \dfrac{\psi_a\,\psi_b}{x_a + x_1 + x_b}$ from Fig. 13, and shown by the intermediate curve C of Fig. 21. Following the same procedure as for a feeder fault, the areas which determine stability are

Area of rectangle $= T_0\,(\delta_2 - \delta_0)$

Area of irregular curve $= T_m\,\{r_1\,(\cos\delta_0 - \cos\delta_1) + r_2\,(\cos\delta_1 - \cos\delta_2)\}$

where $\delta_2 = \pi - \text{arc sin}\,\dfrac{\sin\delta_0}{r_2}$

r_2 = ratio of peak of torque curve following clearance of fault to peak of initial curve.

From the configuration of the areas, it is obvious that more load may be safely carried during short circuits if the fault is rapidly isolated. An example of the method of calculation outlined is given in the Appendix VII.

c. General Case of Two Machines. When it is necessary to take into account other features such as salient pole characteristics, flux decrement, voltage regulators, resistance of lines, governors, and amortisseurs, recourse must be had to a step-by-step method.[*]

The procedure in a study of two machines involving all of the characteristics noted is as follows. The process of simplification is carried out as for the case of two round rotor machines of constant flux linkages. From known voltages, loads, and current or power factor prior to the short circuit, calculate the magnitude and angle from some reference voltage of the flux linkages inside of the transient reactance of the equivalent machine replacing the system. To find the flux linkages of the salient pole machine it is first necessary to find the rotor position with respect to the reference voltage V and this done by adding vectorally to V the quadrature reactance drop between it and the rotor. The quadrature reactance involved consists of the quadrature reactance of the machine plus any additional external reactance between the machine terminals and the point in the system at which the voltage $\dot{V}$ exists. The voltage so determined does not repre-

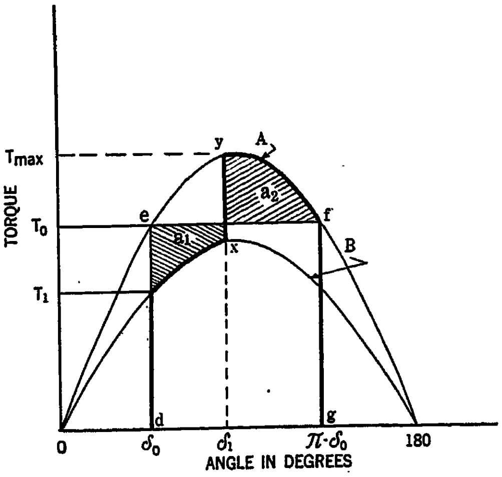

Fig. 20—Effect of Clearing Fault on Feeder

sent any physical quantity, but its angle gives the rotor angle correctly. The angle between the current and the rotor position is next found and i_d is obtained from

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[*] A time interval of 1/20 of a sec. has been satisfactory in most cases.

$i_d = I \sin$ (angle between current and rotor)

On the assumption, which is correct for a salient pole machine that $x_q' = x_q$

The rotor linkages are

$\psi' = V \cos$ (angle between V and rotor) $+ i_d x_d'$ where x_d' is the transient reactance between V and the rotor winding.

The excitation m. m. f. is calculated from

$$I = \psi' + i_d (x_d - x_d')^*$$

Determine the reactance of the shunt simulating the fault for the type of short circuit considered in the manner previously described. The system is then as indicated in the upper Fig. 19, except that x_a should be the reactance from the fault to the machine terminals. By paralleling the shunt and round rotor machine, it becomes the lower Fig. 19.

At the instant of short circuit ψ', ψ_b remain constant; and δ and the new values of i_d and ψ due to the fault are

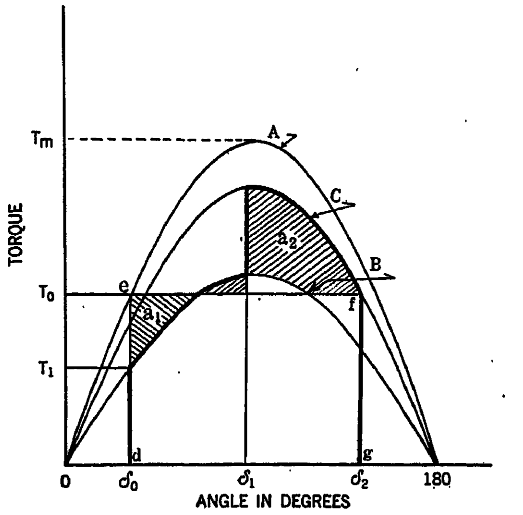

FIG. 21—EFFECT OF CLEARING FAULT ON PARALLEL LINE

$$i_d = \frac{(x_q + x_e)\ (\psi' - \psi_e \cos \delta_e) - r_e \psi_e \sin \delta_e \dagger}{r_e^2 + (x_d' + x_e)\ (x_q + x_e)}$$

$$I = \psi' + i_d (x_d - x_d')$$

Where x_q = quadrature transient reactance of machine alone

x_d' = direct transient reactance

x_d = direct synchronous reactance

$$r_e + j x_e = Z_e = Z_a + \frac{Z_b Z_s}{Z_b + Z_s}$$

Z_a = impedance from salient pole machine to point of fault

Z_b = impedance of equivalent round rotor machine to point of fault

Z_s = impedance of shunt at point of fault

ψ' = flux linkages of salient pole machine

$\psi_e = \psi_b \dfrac{Z_s}{Z_b + Z_s}$ flux linkages of machine replacing short and system

ψ_b = flux linkages of round rotor machine replacing system

δ_e = angle between ψ' and ψ_e

δ = angle between ψ' and ψ_b.

The torque immediately following the fault and at successive intervals may be found in two ways, either by equation or a circle diagram in which the salient pole machine is treated as a round rotor machine having reactance x_q and a fictitious excitation which gives the correct torque and which may be derived from ψ' and ψ_e. If resistance is to be neglected, the torque is the same on both machines and the equation is

$$T = \frac{I \psi_e}{x_d + x_e} \sin \delta_c + \frac{\psi_e^2 (x_d - x_q)}{2\ (x_d + x_e)\ (x_q + x_e)} \sin 2 \delta_e$$

The first term contains the variables I and δ_e and the second term δ_e only. The easiest method of finding the power at each interval is to plot each term as a function of δ_e or δ which differs from δ_e by a constant angle, with I as unity. The second term may then be read directly from the curve for the known angle, while the first term merely requires the multiplication of the curve reading by the value of I at the time.

When resistance is to be included, the torque equations contain a large number of terms and would necessitate much tedious arithmetic at each step, so the circle diagram method is preferable in spite of the increased preliminary work to prepare it.

Using x_q for the salient pole machine and the other circuit constants as in Fig. 19, the general circuit constants are found.‡ From these, torque circles are constructed.

The equation of the receiver torque circles is

$$(T_2 + \psi_b^2 l)^2 + (Q_2 + \psi_b^2 m)^2 = (n\ O\ Q\ \psi_b)^2$$

and of the generator circles is

$$\left(\frac{T_1^2}{O\,Q^2} - l'\right)^2 + \left(\frac{Q_1}{O\,Q^2} - m'\right)^2 = \left(n \frac{\psi_b}{O\,Q}\right)^2$$

These are families of circles having centers $- \psi_b^2 l$, $- \psi_b^2 m$ and l', m' respectively and radii $n\,O\,Q\,\psi_b$ and $n \dfrac{\psi_b}{O\,Q}$ respectively. A number of circles are drawn for various values of $O\,Q$. The terminology used is

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*For a round rotor machine both axes should be considered. However, as the decrement in the quadrature axis is about 4 times that in the direct axis, this refinement is not always essential.

†Bibliography 3 and 5.

‡See table on p. 144 "Electrical Characteristics of Transmission Circuits," by William Nesbit.

T_2 = torque received
Q_2 = reactive kilovolt-ampere received
T_1 = torque generated
Q_1 = reactive kilovolt-ampere generated
$O\,Q$ = fictitious excitation of equivalent round rotor machine

$$l = \frac{a_1 R_0 + a_2 x_0}{R_0^2 + x_0^2}$$

$$m = \frac{a_1 x_0 - a_2 R_0}{R_0^2 + x_0^2}$$

$$n = \frac{1}{\sqrt{R_0^2 + x_0^2}}$$

$$l' = \frac{d_1 R_0 + d_2 x_0}{R_0^2 + x_0^2}$$

$$m' = \frac{d_1 x_0 - d_2 R_0}{R_0^2 + x_0^2}$$

where the general circuit constants are

$A_0 = a_1 + j\,a_2$
$B_0 = R_0 + j\,x_0$
$D_0 = d_1 + j\,d_2$

To complete the diagram, the reference axes for the displacement angles are laid off through the centers of the circles at a clockwise angle from the vertical whose tan is R_0/x_0. The line of zero angle is downward in the generator circles and rotor angles are measured counterclockwise from it. In the receiver circles, it is upward, and angles are measured clockwise from it. For a given $O\,Q$ and δ the per unit receiver torque is read directly, but the number read from the generator circle is multiplied by $O\,Q^2$ to get the per unit torque generated.

The fictitious excitation $O\,Q$ is obtained from the real excitation I from $O\,Q = I - i_d\,(x_d - x_q)$. For the instant following the short circuit i_d has already been calculated so $O\,Q$ is readily found but it is unnecessary to get i_d at later intervals for other purposes. Therefore, the determination of $O\,Q$ is simplified if a curve is plotted of its variation with δ. $O\,Q = k\,I + k_1 \cos \delta_e + k_2 \sin \delta_e$.

Since δ_e differs from δ by a constant angle, the sum of the last two terms may be plotted as a function of δ. At any later time, the first term is obtained from I and the sum of the other two from the curve.

The torque acting to retard or accelerate the rotor is the difference between the mechanical and electrical torques, both of which are complex functions of time and involve governor characteristics, damping action, flux linkages, and angles. The degrees change in angle of each machine during the interval immediately following the short circuit is given by

$$\Delta\,\delta = \left(1 - \frac{F\,\Delta\,t}{4\,M}\right) \frac{360\,f\,\Delta\,t^2}{2\,M}\ (T_0 - G_0)$$

in which
$\Delta\,t$ = time interval in seconds
M = inertia constant of machine
F = per unit damping torque per unit speed change
f = frequency in cycles per second
T_0 = electrical torque at instant after fault
G_0 = mechanical torque at instant of fault

The change of angle of both machines is added to or subtracted from the original angle between the rotors and the angle at $\Delta\,t = 1$ is found. Before calculating the power at this interval a new value of I must be determined from the field decrement, excitation system, and change in armature reaction. A per unit slip-ring volt *vs.* time curves should be plotted from regulator and excitation data and the average value of slip-ring volts during the interval picked out. I will tend to die away from its initial value to that which would be sustained by the slip-ring volts (E) along an exponential curve having a time constant of

$$T_f = T_{f0}\,\frac{x_d' + x_e}{x_d + x_e}$$

where T_{f0} is the time constant of the field with the stator circuit open. For the short intervals used, it will have a value of $I_{B\,(n-1)} = E + \left(1 - \frac{\Delta\,t}{T_f}\right)\ (I - E)$ at the end if i_d did not change. However, i_d does change with rotor position and to determine its effect it is assumed that the rotors suddenly move through the angles $\Delta\,\delta$ at the end of the period. The new value of I is then given by

$$I_{A(n-1)} = I_{B(n-1)} + \frac{\psi_e\,(x_d - x_d')\,\Delta\,\delta\,[\,(x_q + x_e) \sin \delta_{eA} - r_e \cos \delta_{eA}]}{r_e^2 + (x_d' + x_e)\,(x_q + x_e)}$$

where subscript B refers to conditions before rotor angle changed and A applies after the change. Here also a curve of the term

$$\frac{\psi_e\,(x_d - x_d')\,[\,(x_q + x_e) \sin \delta_e - r_e \cos \delta_e)\,]}{r_e^2 + (x_d' + x_e)\ (x_q + x_e)}$$

of δ_e makes the simplest method of using the equation. To $I_{B\,(n-1)}$ is added the difference between the curve readings for δ_{eB} and δ_{eA}. $O\,Q$ is again calculated from $I_{A\,(n-1)}$ and the torques from the circle diagram.

For any other than the first period the angular change is computed as follows. The average per unit change in speed during the preceding interval from $(n-2)$ to to $(n-1)$ is $S_{n-\frac{3}{2}} = \frac{\Delta\,\delta_{n-1}}{360\,f\,\Delta t}$

where $\Delta\,\delta_{n-1}$ is the degree change between $(n-2)$ and $(n-1)$.

The average gate or throttle opening during the same interval cannot be determined so the value at $(n-2)$ must be used. There is

$$G_{n-1} = G_{n-2} + \Delta t \, A \, (G_{n-2}, S_{n-\frac{3}{2}})$$

in which A is a function of G and S and will have to be obtained from the designer of the governor.

$T_{(n-1)}$ is found from the circle diagram or the torque curve

$$\alpha_{(n-1)} = \frac{360 f \, (\Delta t)^2}{M} \, (T_{(n-1)} - G_{(n-1)})$$

$$\Delta \delta_n = \left(1 - \frac{F \, \Delta t}{M}\right) \Delta \delta_{(n-1)} + \left(1 - \frac{F \, \Delta t}{2 M}\right) \alpha_{(n-1)}$$

This process is then repeated as many times as desired.

d. Extension to Include More Than Two Machines. When the system connections are such that two machines will not correctly represent real conditions and three or more must be taken into consideration, the principle of super-position is employed to calculate the currents and torques. The system should be condensed and simplified as much as possible by the combination of equipment into equivalent machines and the replacement of mesh connections by star connections.

The initial flux linkages and angles are determined as described in the section dealing with two machines and also the value of impedances to represent the short circuit. When the connections are complex and resistance is considered, the work of calculating the angle time curve may be shortened by an approximation which consists of putting a single resistor in the fault impedance which would initially have the same losses as the total of the positive, negative, and zero-phase sequence losses if the divisions of current were influenced by reactance only. The value of this resistance is obtained for each of the phase sequence networks by allowing unit current to flow into the fault, finding its division in all the circuits if they had reactance only and finding the total $I^2 R$ losses in them. The resistance which would have the same loss at the point of fault would be the sum of the $I^2 R$ losses divided by the unit I^2 assumed. The value to be placed in the fault impedance is the sum of the three resistors applying to the three-phase sequence networks plus any that may be assumed for the earth and fault itself.

The flux linkages and angles remain unchanged at the instant of short circuit, and the conditions immediately subsequent to the fault are determined by impressing on the circuit each of the machine linkages taken one at a time and considering all the other machines as shunt reactors.*

The current in each branch is the vector sum of the currents caused by the individual application of the flux linkages. From the currents and linkages, the electrical torque may be calculated and from them the angular change of each machine during the time interval. The excitation amperes are obtained by $I = \psi' + i_d (x_d - x_d')$ for each machine and the change in flux linkage if the angle were constant is $\Delta \psi' = \dfrac{1}{T_{f0}} (E_{n-1/2} - I_{n-1}) \, \Delta t$ where T_{f0} is the open circuit time constant, $E_{n-1/2}$ is the average per unit exciter volts during the interval $(n - 1)$ to n and I_{n-1} is the per unit field current at instant $(n - 1)$. There is $\psi_n' = \psi_{n-1}' + \Delta \psi'$. Now let the angles change by the previously calculated amount, impress the individual linkages and find the branch currents, field amperes, and torques and repeat for as many steps as desired.

When the short circuit is removed the circuit constants again change and the problem is treated in just the same manner except that the initial velocities must be included.

e. Simplified Method of Calculating Tie Line. When both of the systems are very large, relative to the power limit of the line alone, an approximate answer may be obtained as follows, without the necessity of the detailed step-by-step calculations.

The maximum power which can be transmitted over a line of this type is approximately

$$V^2 \, \frac{\sqrt{x^2 + r^2} - r}{x^2 + r^2}$$

where r = line resistance
x = line reactance + the transient reactance of each system viewed from its end of the line†
V = line-to-line voltage

We wish to determine, however, the maximum amount of average power which can be sent over the line. To do so, it is essential that some method be available for determining the magnitude of the load surges to be anticipated.

The value of these surges may be calculated from the formula

$$\Delta p = \frac{\dfrac{\Delta f}{f_0}}{\dfrac{\alpha_1}{c_1} + \dfrac{\alpha_2}{c_2}}$$

where f_0 = normal frequency
Δf = the momentary differences in frequency which would exist if the systems were not tied together.
α_1 and α_2 = the average governor regulations of each system.
c_1 and c_2 = the corresponding generating capacities.

The quantity Δf may either be determined from a comparison of frequency charts, or, if it is imagined due to sudden loss of a specific load or generating capacity in either system, may be calculated. For example, the sudden loss of a load ΔL_1, in system 1, would increase

---

*In general, the reactance of each machine will be different in each of its axes.

†Measured by the short-circuit current fed from the system for a three-phase fault at the junction of the line and system.

Δf over what it otherwise would be by an amount

$$\frac{\alpha_1 \, \Delta \, L_1}{c_1}.$$

Under normal conditions of operation quite distinct from emergency conditions, a somewhat unsystematic variation of frequency in a system of about $\frac{1}{4}$ cycles in 60, is to be anticipated even in the best regulated of systems. This means that at best $\frac{\Delta f}{f_0} = \frac{1}{120}$. With normal four per cent governors, this gives the result $\Delta \, p_{min}$ = about $\frac{0.2 \, c_1 \, c_2}{c_1 + c_2}$.

Thus, if both systems are of approximately equal size, the minimum fluctuations to be anticipated are about 10 per cent of the generating capacity of either system, while if one system is much smaller than the other, they may be 20 per cent of the generating capacity of the smaller systems.

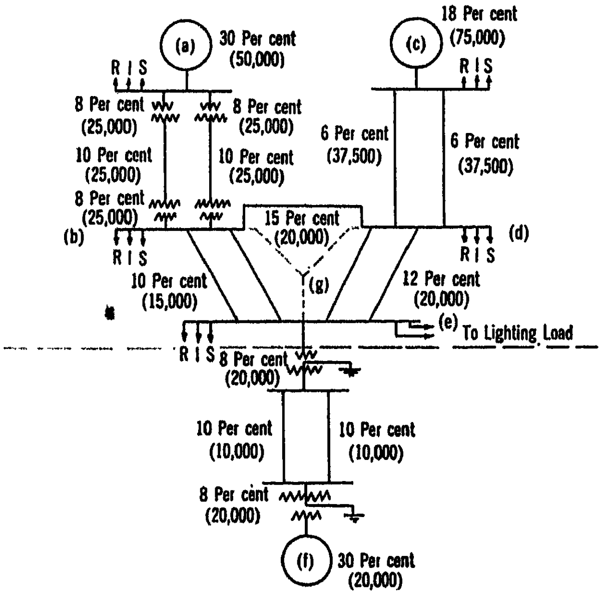

Fig. 22—Assumed System and Proposed Extension used as a Basis for the Sample Calculations

One peculiarity of the type of tie line under consideration is the fact that in general the wattmeters show a more or less steady pulsation of power at the natural frequency, determined by the inertias of the system and the synchronizing power of the line. The magnitude of pulsation seems to be of the order of one-half per cent of the generating capacity of the smaller systems, while the pulsation in itself may not be of significance from the standpoint of pull-out, because of its small magnitude, it can cause inconvenience to customers tapped off near the middle of the line due to the variation of brilliancy of lamps concurrent with the regular pulsation of voltage.

Acknowledgments

The authors wish to express their appreciation of the assistance in the preparation of the paper and many valuable suggestions of Mr. J. B. McClure. They wish also to thank Messrs. R. C. Buell and Alan Howard for their assistance in calculations.

Appendix I

Example to Demonstrate the Application of the Constant Linkage Method to a Proposed Extension—Based on Derivations in the Appendix

In Fig. 22 is shown a fictitious system of generating plants, together with transformer banks and connecting transmission lines. The portion of the system from *e* up constitutes an existing system, and that from *e* down represents a proposed extension to a new hydro station.

Apparatus to be Considered. The generating capacities are as follows

a. 50,000-kv-a. hydro station (existing)
c. 75,000-kv-a. steam station (existing)
f. 20,000-kv-a. hydro station (proposed)

Load centers (1), (2), (3), (4), and (5) are each assumed to consist of:

5000 kw. resistance load
5000 kw. at 0.7 power-factor lag induction motor load
5000 kw. at 0.8 power-factor lead, synchronous motor load.

Hence, each load center is supplying 15,000 kw. at 0.99 power factor lagging or 15,100 kv-a.

In order to assign equivalent reactances and inertia constants to the rotating apparatus of the various loads, the installed kilovolt-ampere capacities of the machines must be determined. In the event no specific data are available, it is reasonable to assume, and very close to operating conditions, that the synchronous motors are operating at half load 0.8 power-factor lead, but with field excitation to give full load 1.0 power factor and the installed kilovolt-ampere capacity will be twice the kilowatt load. Assuming that the 0.7 power-factor lagging induction motor load is composed of

I, motors at no load (synchronous impedance 300 per cent)

II, motors at $\frac{3}{4}$ load, the power factor of these motors being 0.89 lag at full load,

the installed kilovolt-ampere capacity of induction motors is $2\frac{3}{4}$ times the kilowatt load. On this basis, each load center has 13,800-kv-a. induction motors and 10,000-kv-a. synchronous motors, and with this knowledge the proper values of reactances and inertia constants may be chosen from the tables and referred to the assigned base.

Reduction of System to Equivalent Series Reactance. Transient reactances are used for positive phase impedances of rotating machines, except that synchronous reactance is used for the positive reactance of an induction motor.

Negative sequence reactances are used for negative phase impedances of rotating machines except that transient reactance is used for the negative reactance of an induction motor.

See Table V for zero-phase reactances of lines.

In the following calculations, all values of reactance are referring to *100,000-kv-a. base,* while in Fig. 22 the per cent values are given on the base indicated by the number in parenthesis.

Positive Sequence Reactance

$$\text{Generator (a)} = 30 \times \frac{100{,}000}{50{,}000} = 60 \text{ per cent on}$$

100,000 base

In parallel with load (3)

$$\text{Induction motor } 300 \times \frac{100{,}000}{13{,}800} = 2180 \text{ per cent}$$

$$\text{Synchronous motor } 30 \times \frac{100{,}000}{10{,}000} = 300 \text{ per cent}$$

From this the equivalent reactance of generator (a) and load is 48.7 per cent in series with

$$\text{Transformers } \tfrac{1}{2} \times 8 \times \frac{100{,}000}{25{,}000} = 16.0 \text{ per cent}$$

$$\text{Lines } \tfrac{1}{2} \times 10 \times \frac{100{,}000}{25{,}000} = 20.0 \text{ per cent}$$

$$\text{Transformers } \tfrac{1}{2} \times 8 \times \frac{100{,}000}{25{,}000} = \frac{16.0 \text{ per cent}}{100.7 \text{ per cent}}$$

in parallel with load (4)

2180 per cent

300 per cent

= 73.0 per cent which is equivalent positive reactance from point b to generator (a).

Generator (c)

$$= 18 \times \frac{100{,}000}{75{,}000} = 24.0 \text{ per cent in parallel with load.}$$

Induction motors

$$= 300 \times \frac{100{,}000}{13{,}800} = 2180.0 \text{ per cent}$$

Synchronous motors

$$= 30 \times \frac{100{,}000}{10{,}000} = 300 \text{ per cent}$$

From this the equivalent reactance of generator (c) and load

is 22 per cent in series with lines

of 8 per cent gives a total of 30 per cent in parallel with

Synchronous motors 300 per cent

Induction motors 2180 per cent

= 27.2 per cent which is the equivalent positive reactance from point d to generator (c).

Transforming the mesh circuit b, d, e into the equivalent star as indicated by the dotted lines to g

b–g = 75 × 67 ÷ 202 = 24.8 per cent

d–g = 75 × 60 ÷ 202 = 22.3 per cent

g–e = 67 × 60 ÷ 203 = 19.9 per cent

Reactance a–g = 73.0 + 24.8 = 97.8 per cent

Reactance c–g = 27.2 + 22.3 = 49.5 per cent

which equal in parallel................ 32.8 per cent

which has in series g–e giving a total of.. 52.7 per cent

with load in parallel of induction motor. 2180 per cent

synchronous motor. 300 per cent

giving a total of 44 per cent for total equivalent positive reactance of the main system.

The positive reactance of the proposed extension is equal to

$$\text{Generator (f) of } 30 \times \frac{100{,}000}{20{,}000} = 150$$

Transformers 8 × 5 = 40

2 lines in parallel 10 × 5 = 50

Transformers 8 × 5 = 40

280 total,

from which, total positive series reactance between the two systems is equal to 324 = x_1.

Calculation of the equivalent M of the system

By definition M = time for machine to come to rest from synchronous speed with full load torque applied.

Since the reactances have been calculated on a base of 100,000 kv-a., the inertia constants will be referred to the same base.

$$M \text{ of hydro plant (a)} = 6 \times \frac{50{,}000}{100{,}000} = 3.0$$

$$M \text{ of steam plant (c)} = 16 \times \frac{75{,}000}{100{,}000} = 12.0$$

$$M \text{ of resistance load} = 0$$

$$M \text{ of induction motor load} = 1.10 \times \frac{13{,}800}{100{,}000} = 0.152$$

$$M \text{ of synchronous motor load} = 4.5 \times \frac{10{,}000}{100{,}000} = 0.450$$

M_2 = total M of main system

$= 3.0 + 12.0 + 5 \times 0.152 + 5 \times 0.450 = 17.8$

$$M_1 = M \text{ of extension} = 6 \times \frac{20{,}000}{100{,}000} = 1.2$$

M_0 = equivalent M which is assigned to the extension in order that the relative oscillation will be similar while the main system is assumed to be infinitely stable.

$$\frac{1}{M_0} = \frac{1}{M_1} + \frac{1}{M_2} \therefore M_0 = \frac{1.2 \times 17.8}{19.0} = 1.13$$

Initial Conditions. The torque at any relative rotor position is given by $\dfrac{\psi_a \, \psi_b}{x} \sin \delta$ where ψ_a and ψ_b are the flux linkage voltages or voltages behind transient reactance. It is, therefore, necessary to determine these flux voltages for various loads which may be carried while a terminal voltage is maintained constant at some point in the system which is chosen here as point e.

Assuming a voltage $E = 1.0 + j\,0.0$ at e and a load of 10,000 kw. at 0.99 power-factor lag, which is the power factor of the assumed system load

$$\psi_b = 1.0 + j\,0.0 - j\,.44\left[\frac{10{,}000}{100{,}000} - j\,\frac{1423}{100{,}000}\right]$$

$$= 0.995 \,/\overline{2.5^\circ}$$

$$\psi_a = 1.0 + j\,0.0 + j\,2.8\left[\frac{10{,}000}{100{,}000} - j\,\frac{1423}{100{,}000}\right]$$

$$= 1.073 \,\underline{/\,15.1^\circ}$$

Under this load condition, which results in the above flux voltages, the maximum instantaneous torque which can be developed at synchronous speed is equal to $\dfrac{1.073 \times 0.995}{324.0} \times 100 = 0.33$ times the base kilovolt-ampere = 33,000 synchronous kilowatts.

In Fig. 23 a curve is plotted of maximum torque for various values of load on the machine. These loads determine the flux voltages ψ_a and ψ_b and also the angle δ at which the machine must be operating to supply that load.

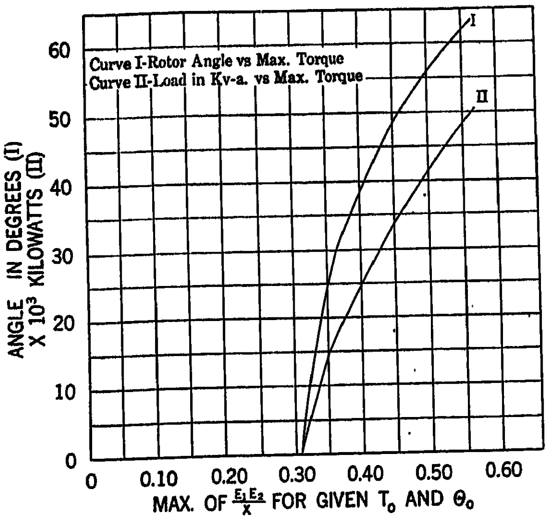

FIG. 23—CURVES OF MAXIMUM SYNCHRONOUS TORQUE AS A FUNCTION OF INITIAL LOAD AND INITIAL ANGLE

Maximum Load which May be Suddenly Applied. The machine is delivering 10,000 kw. which is 0.303 of the maximum and has, therefore, an internal angle of $\delta = \sin^{-1} 0.303 = 17.6$ degrees.

From the curve in Fig. 12 the maximum additional load which may be thrown on and have stability maintained is $0.508 \times 33{,}000 = 16{,}800$ kw., making a total load of 26,800 kw.

Opening a Parallel Line. With both parallel lines carrying power, the total equivalent positive sequence series reactance is 324 per cent, but with one line open and power going over the remaining one only, the series reactance is equal to 374 per cent. It is seen then that with one line only carrying power, the maximum torque is less than with both lines in. The ratio of

$$\frac{\text{max. torque one line}}{\text{max. torque two lines in parallel}} = 0.865.$$

From curve 14 it is noted that the system could have been carrying 0.833 of the original maximum torque. From curve 23 the maximum torque, due to the rotor being at an angle $\theta = \sin 0.833 = 56.5$ deg. and with a corresponding excitation to maintain a voltage E at e under this load condition is 49,500 kw. The initial load which could be safely carried while one line is opened is $0.833 \times 49{,}500 = 41{,}100$ kw.

Line to Ground Short Circuit Maintained on the High-Tension Side of the Transformer Bank at the Generator End. The negative phase sequence equivalent reactance of the main system as calculated is 27.7 per cent, and the total negative sequence reactance of the system as viewed from the point of short circuit is $27.7 + 40 + 50$ in parallel with $200 + 40 = 79.0$ per cent.

The zero sequence reactance of the system viewed from the point of short circuit consists of 40 per cent in parallel with

40 per cent + 5 × 50 per cent = 35.2 per cent

x_a = pos. reactance from gen. to short circuit = 190 per cent

x_b = pos. reactance from main system to short circuit = 134

$x = x_2 + x_0 = 79.0 + 35.2 = 114.2$

The equivalent series reactance now is equal to

$$x_a + x_b + \frac{x_a\,x_b}{x} = 545 \text{ per cent}$$

Hence, with the short maintained, the maximum torque is 0.595 of the original. Under these conditions from curves (Fig. 14) and (Fig. 23) the maximum initial load that can safely be carried when the short circuit is applied and maintained is

$$0.517 \times 36{,}500 = 18{,}900 \text{ kw.}$$

Short Circuit Maintained on the High-Tension Side of the Transformer Bank at the System End.

x_a = positive reactance from generator to short circuit = 240 per cent

x_b = positive reactance from main system to short circuit = 8 per cent

$x = x_2 + x_0 = 55.0 + 35.2 = 90.2$ per cent

The equivalent series reactance is equal to 547 per cent and from this the ratio of torque angle curves with or without the short circuit is 0.590. Under these conditions from curves (Fig. 14) and (Fig. 23) the maximum initial load than can safely be carried when the short circuit is applied and maintained is

$$0.512 \times 36{,}300 = 18{,}600 \text{ kw.}$$

Short circuit maintained in the middle of the line section on one conductor only.

$x_a = 215$ $x_0 = 114$
$x_b = 109$ $x_2 = 81.5$
$x = x_0 + x_2 + x_{1c}$ $x_{1e} = 12.5$ which must be added as a result of the short occurring out on the line.

$$\text{The equivalent series reactance} = 324 + \frac{215 \times 109}{208}$$

= 437 per cent and from this the ratio of the peaks of the torque angle curves is $\frac{324}{437} = 0.742$. Under these conditions, from curves (Fig. 14) and (Fig. 23) the maximum initial load which can be safely carried when the short circuit is applied and maintained is

$$0.68 \times 41{,}300 = 28{,}000 \text{ synchronous kw.}$$

The curve in Fig. 24 shows how the maximum power which may be safely carried varies with the location of the line to ground short circuit on one of two parallel lines and Fig. 25 shows the variation in zero-phase sequence reactance as a function of the point of fault along the line.

Effect of Speed of Switching on Maximum Load which can be Carried throughout the Disturbance Caused by a Short Circuit on an Interconnecting Line. In this example, the short circuit is assumed to occur on the high-tension side of the transformer bank at the main system end of the extension. In this case, if the system has a maximum torque of 1.0 before the short circuit, the maximum torque with the short circuit will be 0.59, and after the short circuit has been cleared by opening the parallel line, the maximum is 0.865. These conditions give the more general case of dealing with three torque angle curves to obtain the solution, while if the short circuit occurred on a spur line as indicated coming from the interconnecting bus, the system would return to the initial torque angle curve after the short circuit had been cleared.

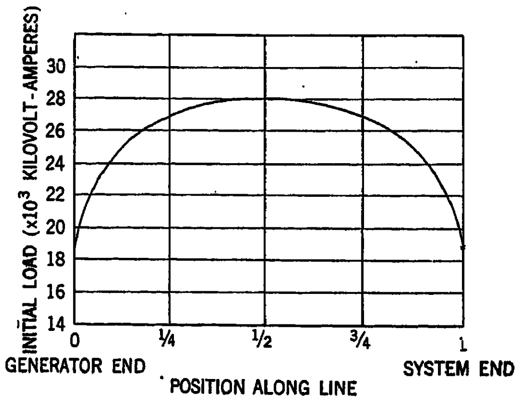

FIG. 24—MAXIMUM INITIAL LOAD WHICH MAY BE CARRIED THROUGH SUSTAINED LINE TO GROUND FAULT AS A FUNCTION OF POSITION OF FAULT

With an initial torque of 0.75 and a corresponding angle $\delta_0 = 48.8$ deg., the angle δ_1 is solved for as the angle at which the breaker must open to maintain stability.

δ_2 is the maximum angle to which the machine can swing with stability on curve *C*

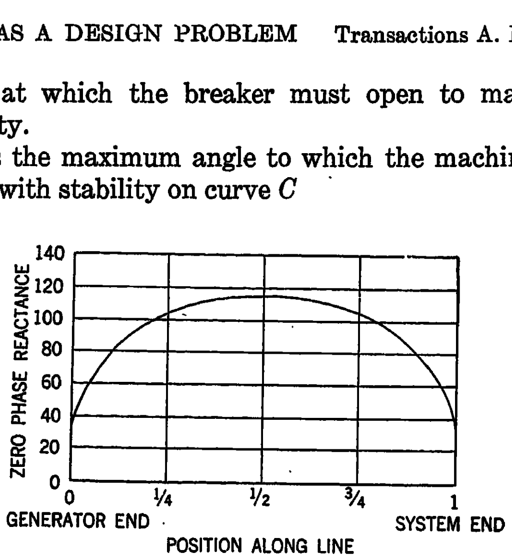

FIG. 25—ZERO-PHASE SEQUENCE REACTANCE AS A FUNCTION OF POSITION OF LINE TO GROUND FAULT

$$\delta_2 = \pi - \sin^{-1}\frac{0.75}{0.865} = \pi - 60 = 120 \text{ deg.}$$

$$\begin{aligned}
\sin\delta_0 &= 0.75\\
\cos\delta_0 &= 0.662\\
\cos\delta_2 &= -0.500\\
r_1 &= 0.590\\
r_2 &= 0.865\\
\delta_2 - \delta_0 &= 1.242 \text{ radians}
\end{aligned}$$

$$\cos\delta_1 = \frac{0.75 \times 1.242 - 0.590 \times 662 - 0.866 \times 0.500}{0.865 - 0.590}$$

$$= 0.404$$

$\delta_1 = 66.1$ deg. which is 17.3 deg. behind the initial position.

It is still necessary to determine what time it takes for the machine to travel this 17.3 deg. and this is determined from the angle time curves.

The initial torque is 0.75 and the equivalent total torque which the machine is advancing to supply on the "B" torque angle curve is $\frac{0.75}{0.59} = 1.27$ of its maximum which is still 0.75 of the initial maximum. From the angle time curves, Fig. 18, it is seen that the machine will have advanced to $\delta = 66.1$ when

$$\text{Time in seconds} = \frac{F\left(\delta, \frac{T_1}{T_m}, \frac{T_0}{T_m}\right) = 1.66}{\sqrt{\frac{4\pi f \psi_1 \psi_2}{M_0 x}}}$$

From curve (Fig. 23) the initial conditions give a maximum torque $= \frac{\psi_a \psi_b}{x}$ of 44,500 kw. = 0.445 of the maximum which is taken as unity so that

$$t = \frac{1.66}{\sqrt{\frac{4\pi \times 60 \times 0.445}{1.13}}} = 0.097 \text{ secs.}$$

Several points have been obtained in a similar manner from which the curve in Fig. 26 was plotted. It is seen that the system could safely have been carrying 18,500 kw. and be stable with the short circuit maintained, and also that unless the speed of switching is of the order of a ¼ of a sec. or less, the initial safe power limit is not increased appreciably, in this case.

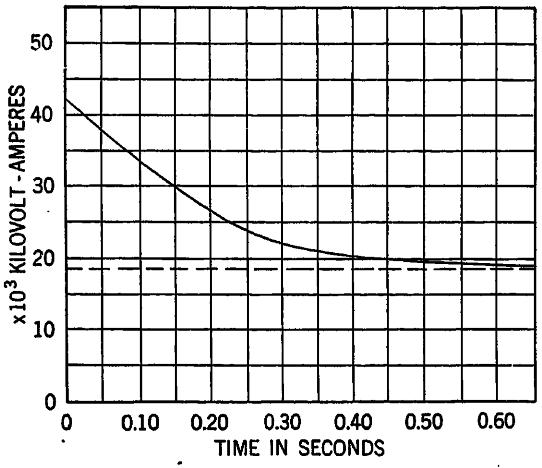

FIG. 26—MAXIMUM INITIAL LOAD WITH STABILITY AS A FUNCTION OF SPEED OF CLEARING FAULT

Appendix II

CALCULATION OF ZERO-PHASE SEQUENCE REACTANCE

Single Circuit Reactance. The zero-phase sequence reactance of a transmission line is the reactance of all the conductors in parallel with a ground return. This reactance is referred to the current in one phase only, that is, to one-third of the total ground current. Let the conductors be termed a, b, and c, the ground wire d, and their images a' b' c' and d'. The distance to the image depends on soil conditions. Tests indicate that this is generally 1000-5000 ft. The flux linkages with conductor a per unit length of line are

$$\psi_a = 2\,I_a \log \frac{a\,a'}{r_a} + 2\,I_b \log \frac{a\,b'}{a\,b} + 2\,I_c \log \frac{a\,c'}{a\,c} + 2\,I_d \log \frac{a\,d'}{a\,d}$$

For the zero-phase network

$I_a = I_b = I_c = I_0$ If the conductors are completely transposed.

$I_d = -\,m\,I_0$

$K_{aa} = 2 \log \dfrac{a\,a'}{r_a}$ = coefficient of self inductance of conductor a.

$K_{ab} = 2 \log \dfrac{a\,b'}{a\,b}$ etc., coefficients of mutual inductance of conductors a and b, etc.

The equations for the flux linkages about the several conductors may now be written.

$$\psi_a = I_0\,(K_{aa} + K_{ab} + K_{ac} - m\,K_{ad})$$
$$\psi_b = I_0\,(K_{ab} + K_{bb} + K_{bc} - m\,K_{bd})$$
$$\psi_c = I_0\,(K_{ac} + K_{bc} + K_{cc} - m\,K_{cd})$$
$$\psi_d = I_0\,(K_{ad} + K_{bd} + K_{cd} - m\,K_{dd})$$
$$\psi_0 = \frac{\psi_a + \psi_b + \psi_c}{3}$$

Let $K_{aa} + 2\,K_{ab} + 2\,K_{ac} + K_{bb} + 2\,K_{bc} + K_{cc} = K_{00}$.

Then $K_{00}\,I_0 - m\,(K_{ad} + K_{bd} + K_{cd})\,I_0 = 3\,\psi_0$

$$\psi_d = (K_{ad} + K_{bd} + K_{cd} - m\,K_{dd})\,I_0$$

Neglecting resistance* we may say that $\psi_d = 0$ because the ground wires are connected to each tower.

$$m = \frac{(K_{ad} + K_{bd} + K_{cd})}{(K_{dd})}\,I_0$$

$$K_{00} - \frac{(K_{ad} + K_{bd} + K_{cd})^2}{K_{dd}} = \frac{3\,\psi_0}{I_0} = 3\,L_0$$

This gives the inductance in abhenrys per cm.

$$\frac{30.48 \times 5280}{10^9}\,2\,\pi\,f\,L_0 = x_0 \text{ in ohms per mile.}$$

The current returning in the ground wire is found from the equation

$$I_{gw} = \frac{(K_{ad} + K_{bd} + K_{cd})}{K_{dd}}\,I_0$$

Twin Circuit Reactance. In general the zero-phase sequence reactance of a system, viewed from a point of fault, is low in the neighborhood of any grounded neutral transformer banks and tends to increase as the distance of the fault from such grounding points increases.

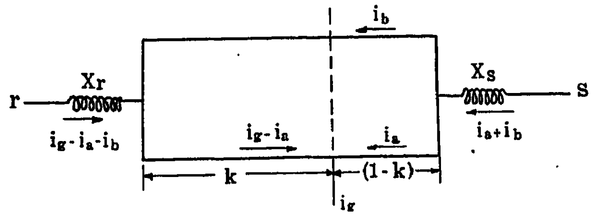

FIG. 27—DISTRIBUTION OF ZERO-PHASE SEQUENCE CURRENTS IN TWO PARALLEL LINES

The distribution of zero phase reactance, along two or more parallel lines, is in general as in Fig. 25. This variation may be scaled off roughly from a knowledge of the zero phase ohms per mile of one line alone, and of several lines in parallel.

Referring to Fig. 27, for a fault distant k from the r end of the line in per unit of the total length of line there will be no flow of zero-phase sequence current in any line but that on which the fault occurs if

---

*A non magnetic wire is assumed. Steel ground wires apparently have little effect on zero-phase sequence reactance.

$$k = \frac{x_{0r}}{x_{0r} + x_{0s}}$$

Where x_{0r} = zero phase sequence reactance of terminal apparatus at the r end

x_{0s} = zero phase sequence reactance of terminal apparatus at the s end

Since in this case the mutual effect of the current returning to r will be proportional to

$$\frac{k}{x_{0r} + k\,x_{0e}} = \frac{1}{x_{0r} + x_{0s} + x_{0e}}$$

Where x_{0e} = zero phase sequence reactance of 1 line.

While the mutual effect due to the current returning to s will be equal and opposite and therefore the voltage at each terminal will be equal; *i. e.*,

$$\frac{x_{0r}}{x_{0r} + k\,x_{0e}} = \frac{x_{0r} + x_{0s}}{x_{0r} + x_{0s} + x_{0e}} = \frac{x_{0s}}{x_{0s} + (1 - k)\,x_{0e}}$$

The reactance at this point is readily found to be

$$x_{0k} = \frac{x_{0r}\,x_{0s}\,(x_{0r} + x_{0s} + x_{0e})}{(x_{0r} + x_{0s})^2}$$

On the other hand for a short at the r end of the line it is equal to the r end terminal apparatus reactance in parallel with the zero phase reactance of all the lines in parallel plus the s end terminal reactance. Thus, the reactance may be determined at three points and it is often sufficient to approximate the intermediate points. In general, however, a more accurate calculation may be desirable.

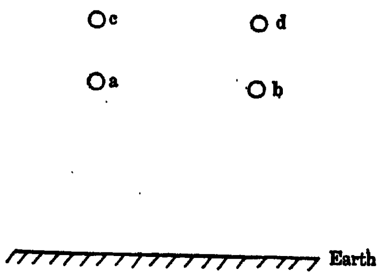

FIG. 28—EQUIVALENT CONDUCTOR ARRANGEMENT OF TWIN CIRCUIT LINE WITH TWO GROUND WIRES

The problem of performing such a calculation is much simplified if the n_1 conductors of each line and the n_2 ground wires over each line are each replaced by equivalent single conductors. If there are sufficient transpositions[*] this may be correctly accomplished by taking the n^2 root of the product of 0.779 times the conductor radii times the distances between the center of the conductor and all the other conductors times the same terms for each of the other conductors, *i. e.*, for a three conductor line

$$r_0 = \sqrt[9]{0.779^3 \times r^3 \times s_{12}^2 \times s_{13}^2 \times s_{28}^2}.^*$$

If there are two or more ground wires, they are similarly treated and the radius of the equivalent ground wire determined.

The effective distance between the equivalent ground wire and equivalent line is given by the $n_1\,n_2$ root of the $n_1\,n_2$ terms in the product of all the distances between line and ground wire conductors. Similarly, the effective distance between equivalent lines is the n_1^2 root of the n_1^2 terms formed by the product of all the distances from the conductors of one line to the conductors of the other and vice versa.

The twin circuit line and its ground wire is then represented by four wires as in Fig. 28.

The flux linkage equations of the four conductors are:

$$\begin{aligned}
\psi_a &= K_{aa}\,i_a + K_{ab}\,i_b + K_{ac}\,i_c + K_{ad}\,i_d \\
\psi_b &= K_{ab}\,i_a + K_{bb}\,i_b + K_{bc}\,i_c + K_{bd}\,i_d \\
\psi_c &= K_{ac}\,i_a + K_{bc}\,i_b + K_{cc}\,i_c + K_{cd}\,i_d = 0 \\
\psi_d &= K_{ad}\,i_a + K_{bd}\,i_b + K_{cd}\,i_c + K_{dd}\,i_d = 0
\end{aligned}$$

The last two are equal to zero since the ground wires are assumed to be at ground potential everywhere and no voltage drop is assumed in the earth. Solving them for i_c and i_d and recalling that for symmetrical lines

$$\begin{aligned}
K_{cc} &= K_{dd} \\
K_{ac} &= K_{bd} \\
K_{ad} &= K_{bc}
\end{aligned}$$

There is

$$\begin{aligned}
i_c &= -\frac{(K_{ac}\,K_{cc} - K_{ad}\,K_{cd})\,i_a + (K_{ad}\,K_{cc} - K_{cd}\,K_{ac})\,i_b}{K_{cc}^2 - K_{cd}^2} \\
&= -\,(J_{ac}\,i_a + J_{bc}\,i_b) \\
i_d &= -\frac{(K_{ad}\,K_{cc} - K_{ac}\,K_{cd})\,i_a + (K_{ac}\,K_{cc} - K_{cd}\,K_{ad})\,i_b}{K_{cc}^2 - K_{cd}^2} \\
&= -\,(J_{ad}\,i_a + J_{bd}\,i_b) \\
i_d &= -\,(J_{bc}\,i_a + J_{ac}\,i_b) \\
\psi_a &= (K_{aa} - K_{ac}\,J_{ac} - K_{ad}\,J_{bc})\,i_a \\
&\qquad + (K_{ab} - K_{ac}\,J_{bc} - K_{ad}\,J_{ac})\,i_b \\
&= K_{aa}'\,i_a + K_{ab}'\,i_b \\
\psi_b &= K_{ab}'\,i_a + K_{aa}'\,i_b
\end{aligned}$$

Then if k is the distance from the r end of the line in per unit of the total line length, and if

V_A = total voltage induced from line A to ground

V_B = total voltage induced from line B to ground

there is

$$\begin{aligned}
V_A &= c\,(K_{aa}'\,i_a + K_{ab}'\,i_b - k\,K_{aa}'\,i_g) \\
V_B &= c\,(K_{ab}'\,i_a + K_{aa}'\,i_b - k\,K_{ab}'\,i_g) \\
V_A - V_B &= (K_{aa}' - K_{ab}')(i_a - i_b) - k\,i_g(K_{aa}' - K_{ab}') = 0 \\
i_a - i_b &= k\,i_g \\
i_b &= i_a - k\,i_g
\end{aligned}$$

where $c = \dfrac{30.48 \times 5280}{10^9}\,2\,\pi f \times$ (length of line in miles)

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[*] Ground wires of course cannot be transposed but there is still no error if there are two ground wires symmetrically placed. In the general case the error is small.

$$3\,V_0 = x_{r0}\,(i_g - i_a - i_b) + c\,3\,k\,[K_{aa}'\,(i_g - i_a) - K_{ab}'\,i_b]$$
$$= x_{s0}\,(i_{sa} + i_{ba}) + c\,3\,(1-k)\,(K_{aa}'\,i_a + K_{ab}'\,i_b)$$
$$3\,V_0 = x_{r0}\,[(1+k)\,i_g - 2\,i_a] + c\,3\,k\,[(K_{aa}' + k\,K_{ab}')\,i_g - (K_{aa}' + K_{ab}')\,i_a]$$
$$3\,V_0 = x_{s0}\,(2\,i_a - k\,i_g) + c\,3\,(1-k)\,[(K_{aa}' + K_{ab}')\,i_{a0} - k\,K_{ab}'\,i_g\,]$$
$$= c\,[\,K_{1a}\,i_a + K_{gr}\,i_g\,]$$
$$= c\,[\,K_{1b}\,i_a + K_{gs}\,i_g\,]$$
$$i_a = \frac{K_{gs} - K_{gr}}{K_{1a} - K_{1b}}\,i_g$$
$$3\,V_0 = \frac{K_{1a}\,K_{gs} - K_{1b}\,K_{gr}}{K_{1a} - K_{1b}}\,i_g = x_0\,i_g$$
$$x_0 = \frac{K_{1a}\,K_{gs} - K_{1b}\,K_{gr}}{K_{1a} - K_{1b}}$$

where,

$$K_{1a} = -\,2\,x_{r0} - c\,3\,k\left[(K_{aa} + K_{ab} - \frac{(K_{ac} + K_{ad})^2}{K_{cc} + K_{cd}}\right]$$

$$K_{gr} = x_{r0}\,(1+k) + c\,3\,k\left[(K_{aa} + k\,K_{ab}) - \frac{K_{cc}\,(K_{ac}^2 + K_{ad}^2 + 2\,k\,K_{ac}\,K_{ad})}{K_{cc}^2 - K_{cd}^2} + \frac{K_{cd}\,(k\,K_{ac}^2 + k\,K_{ad}^2 + 2\,K_{ac}\,K_{ad})}{K_{cc}^2 - K_{cd}^2}\right]$$

$$K_{1b} = 2\,x_s + c\,3\,(1-k)\,.\left[(K_{aa} + K_{ab} - \frac{(K_{ac} + K_{ad})^2}{K_{cc} + K_{cd}}\right]$$

$$K_{gs} = -\,k\,x_s - 3\,c\,(1-k)\,k\left[K_{ab} + \frac{K_{cd}(K_{cd}(K_{ac}^2 + K_{ad}^2) - 2K_{ac}K_{ad}\,K_{cc})}{K_{cc}^2 - K_{cd}^2}\right]$$

x_0 = zero phase sequence reactance to the point of fault.

Appendix III

CORONA LIMITS UNDER UNBALANCED CONDITIONS

The corona limit of a line under unbalanced conditions may be found in terms of its corona limit under balanced conditions, and from the maximum ratio of unbalanced to balanced charging current of any wire.

For example, with normal line-to-line voltage maintained, it was found in a specific case that with one wire grounded the charging currents on the ungrounded wires were 1.50 times their value under normal conditions. This indicated, then, that the maximum line to line voltage to avoid corona under the unbalanced condition was 1/1.50 times the corresponding value under normal condition of operation.

In most cases the ratio referred to is less than 1.50, as shown by the table below.

	Volts kv.	Ratio
Conductors—795,000 cir. mils A. C. S. R. 1.14 in. diam. 25.5 ft. flat spacing two ground wires 184,000 cir. mils A. C. S. R. 0.707 in. diam. spaced 25.5 ft. horizontal 17 ft. above conductors	220	1.50
Conductors same as above but no ground wires	220	1.43
Conductors as above but spaced 32.1 ft. delta. No ground wires	220	1.4
Conductors 4/0 copper 0.528 in. diam. Spaced 6.3 ft. flat. No ground wires	66	1.27

Appendix IV

ANGLE—TIME CURVES

Considering the case of a suddenly applied load to a definite reactance machine connected to an infinite bus by a line, the "per unit" equation of motion is

$$\frac{M}{2\,\pi\,f} \times \frac{d^2\,\delta}{d\,t^2} = T_1 - \frac{\psi_a\,\psi_b}{x}\sin\delta$$

where from Fig. 11

$$T_1 = \text{new total torque}$$

$$\frac{\psi_a\,\psi_b}{x}\sin\delta = \text{machine torque at angle } \delta$$

Integrating with respect to δ and separating the variables gives

$$t = \int_{\delta_0}^{\delta} \frac{d\,\delta}{\sqrt{\frac{4\,\pi\,f}{M}\left[T_1\,\delta + \frac{\psi_a\,\psi_b}{x}\cos\delta - \left(T_1\,\delta_0 + \frac{\psi_a\,\psi_b}{x}\cos\delta_0\right)\right]}}$$

$$\text{but } T_1 = \frac{\psi_a\,\psi_b}{x}\sin\delta_1$$

$$\text{so that } F\left(\delta, \frac{T_1}{T_m}, \frac{T_0}{T_m}\right) = t\sqrt{\frac{4\,\pi\,f}{M}\;\frac{\psi_a\,\psi_b}{x}}$$
$$= \int_{\delta_0}^{\delta} \frac{d\,\delta}{\sqrt{\sin\delta_1\,(\delta - \delta_0) + (\cos\delta - \cos\delta_0)}}$$

The angle—time curves in Figs. 15, 16, 17, and 18 were plotted for several values of T_1 with

$$T_0 = 0;\ 0.25;\ 0.50, \text{ and } 0.75 \text{ respectively.}$$

These curves apply to any machine where all values are expressed in a common base as "per unit"; time being obtained from the abscissas by dividing by

$$\sqrt{\frac{4\,\pi\,f}{M}\;\frac{\psi_a\,\psi_b}{x}}$$

Appendix V

MAXIMUM ADDITIONAL LOAD WHICH MAY BE SUDDENLY APPLIED WITH A GIVEN INITIAL LOAD

Referring to Fig. 11 where

T_0 = initial torque with the corresponding initial angle δ_0

T_1 = new total torque resulting from additional load and δ_1 the corresponding angle

For stability the area $a_2 > a_1$ and the stability limit occurs when $a_2 = a_1$ or when the area of the rectangle is equal to the area under the curve so that

$$\frac{\psi_a\,\psi_b}{x}\sin\delta_1\,(\pi-\delta_1-\delta_0) = \frac{\psi_a\,\psi_b}{x}\int_{\delta_0}^{\pi-\delta_1}\sin\delta\,d\,\delta$$

from which

$$(\pi-\delta_0-\delta_1)\sin\delta_1 = \cos\delta_0 + \cos\delta_1$$

The curve in Fig. 12 was plotted from a graphical solution of the above equation for various values of δ_0. The equation of this curve is approximately

$\Delta\,T = 0.75\,(T_m - T_0)$

where

$\Delta\,T$ = maximum safe additional load which may be suddenly applied

T_m = maximum torque

T_0 = initial torque.

Appendix VI

MAXIMUM INITIAL LOAD WITH STABILITY ON OPENING A PARALLEL LINE

Referring to Fig. 13, curve A is the torque-angle characteristic of the system with both lines in parallel and curve B with one line open. If the system is initially carrying a load of T_0 and one line is opened the problem resolves itself into the sudden application of a load $\Delta\,T$ with an initial load of T_1. The relation between these is given by the following:

$$\frac{T_1}{T_0} = \frac{T_1}{T_1+\Delta\,T} = r \text{ from which}$$

$$\Delta\,T\,r = T_1\,(1-r)$$

For values of r between 1.0 and 0 the curve in Fig. 12 was used to determine values of T_1 and $\Delta\,T$ to give stability. The corresponding T_0 was then expressed in terms of the maximum of curve B. These results are plotted in Fig. 14, and the approximate equation of this curve is

$T_0 = T_m\,(0.7 + 0.3\,r)$

where T_0 = initial torque

T_m = max. torque with one line (curve B)

r = ratio B_{max}/A_{max}.

Appendix VII

THE EFFECT OF CLEARING A LINE TO GROUND SHORT CIRCUIT ON AN INTERCONNECTING LINE

Consider the system in Fig. 13 operating initially at a load T_0 and angle δ_0. The torque angle characteristic as shown by curve A Fig. 21 is $T = \dfrac{\psi_a\,\psi_b}{x}\sin\delta$ where x is the total series reactance. With the short circuit the torque angle characteristic as shown by curve B Fig. 21 is $T = \dfrac{\psi_a\,\psi_b}{x}\sin\delta$ where x is the equivalent series reactance $= x_a + x_b + \dfrac{x_a\,x_b}{x}$ (see Fig. 19). With the short circuit cleared by opening one of the parallel lines the torque angle characteristic as shown by curve C Fig. 21 is $T = \dfrac{\psi_a\,\psi_b}{x}\sin\delta$ where x is the new total series reactance. δ_1 is the position angle of the machine where the fault is cleared and δ_2 is the maximum angle to which the machine can swing on curve C with stability and an initial load T_0.

Stability will result if $a_2 > a_1$ and the limit of stability occurs when the area of the rectangle equals the area under the irregular curve given by

$$\sin\delta_0\,[\pi-\delta_0-(\pi-\delta_2)] = r_1\int_{\delta_0}^{\delta_1}\sin\delta\,d\,\delta + r_2\int_{\delta_1}^{\delta_2}\sin\delta\,d\,\delta$$

from which

$$(\delta_2-\delta_0)\sin\delta_0 = r_1\,[-\cos\delta_1+\cos\delta_0]+r^2[-\cos\delta_2+\cos\delta_1]$$

where r_1 = ratio $\dfrac{B_{max}}{A_{max}}$

r_2 = ratio $\dfrac{C_{max}}{A_{max}}$

No attempt has been made to present results which would be of general use due to the difficulty in choosing general conditions with so many variables.

Appendix VIII

TIME OF BREAKER OPENING AFTER LINE TO GROUND FAULT OCCURS ON A PARALLEL LINE VERSUS MAXIMUM LOAD WHICH MAY BE CARRIED THROUGH THE DISTURBANCE

Possibly the simplest method of attacking this problem is to assume an initial load T_0; that a line to ground fault occurs causing the system to operate on a new torque angle characteristic as shown in curve B, Fig. 21, with an initial load of T_1, and a new applied load T_0; to determine the angle δ_1 at which the breaker must open to maintain stability by allowing the system to operate on a new torque angle characteristic (curve C) with the limit of swing δ_2.

The stability limit occurs when $a_2 = a_1$ and from appendix VII

$$\cos\delta_1 = \frac{\sin\delta_0\,(\delta_2-\delta_0) - r_1\cos\delta_0 + r_2\cos\delta_2}{r_2 - r_1}$$

δ_0 = initial angle of rotor for T_0

δ_1 = angle of rotor when breaker opens

$\delta_2 = \pi - \sin^{-1}\dfrac{T_0}{r_2}$

For various initial loads the maximum value of Curve A may be determined. A similar curve for the example in Appendix I is shown in Fig. 23. From the angle time curves in Figs. 15, 16, 17, and 18 by interpolation, the time may be found that the machine requires to advance to the angle δ_1 for the assumed initial and equivalent applied torque.

initial torque $\sin \delta_0 = T_1$ on Curve B

total torque $T_1 = T_1 / r_1$ in per unit of B_{max}.

$$\text{time} = \frac{F\left(d, \dfrac{T_1}{T_{max}}, \dfrac{T_0}{T_m}\right)}{\sqrt{\dfrac{4\,\pi\, f\, \psi_a\, \psi_b}{M\, x}}}$$

This has been carried through completely in the example given in Appendix I from which the curve in Fig. 26 was plotted.

Appendix IX

DERIVATIONS OF EFFECT OF ROTATIONS ON FIELD CURRENT

As given in the paper, there is,

$$I_A = \psi_d' + i\, d_A\, (x\, d - x\, d')$$

$$I_B = \psi_d' + i\, d_B\, (x\, d - x\, d')$$

$$I_A = I_B + (x\, d - x\, d')\, (i\, d_A - i\, d_B)$$

but

$$i\, d_A = \frac{(x\, q + x\, e)\, (\psi' - \psi_e \cos \delta_{eA}) - r\, e\, \psi_e \sin \delta\, e_A}{r\, e^2 + (x\, d' + x\, e)\, (x\, q + x\, e)}$$

$$i\, d_B = \frac{(x\, q + x\, e)\, (\psi' - \psi_e \cos \delta e_B) - r\, e\, \psi_e \sin \delta\, e_B}{r\, e^2 + (x\, d' + x\, e)\, (x\, q + x\, e)}$$

$i\, d_A - i\, d_B =$

$$\frac{\psi_e[(x\, q + x_e)(\cos \delta\, e_B - \cos \delta\, e_A) + r\, e(\sin \delta\, e_B - \sin \delta\, e_A)]}{r_e^2 + (x\, d' + x_e)\, (x\, q + x_e)}$$

but $\cos \delta\, e_A - \cos \delta\, e_B = -\, [\sin \delta\, e_B]\, \Delta\, \delta$

$\sin \delta\, e_A - \sin \delta\, e_B = [\cos \delta\, e_B]\, \Delta\, \delta$

thus,

$$I_A = I_B + \frac{\psi_e\, \Delta\, \delta\, (x\, d - x\, d')}{r_e^2 + (x\, d' + x\, e)\, (x\, q + x\, e)}$$

$$[\, (x\, q + x\, e) \sin \delta\, e_B - r\, e \cos \delta\, e_B]$$

Appendix X

DERIVATION OF FORMULA FOR VOLTAGES TO GROUND ON THE OPEN PHASES OF A Δ - Y TRANSFORMER BANK WITH A LINE TO GROUND FAULT AND IMPEDANCES IN THE NEUTRAL

Referring to the diagram in Fig. 7, assuming an infinite bus, as shown maintaining balanced voltages and using the method of symmetrical components.

$$I_1 = I_2 = I_0 = \frac{I_g}{3} = \frac{E_1}{Z_1 + Z_2 + Z_0}$$

where

$$Z_1 = Z_e + Z_t$$

$$Z_2 = Z_e + Z_t$$

$$Z_0 = Z_t + 3\, Z_n$$

But

$$V_a = V_1 + V_2 + V_0$$

$$V_b = a^2\, V_1 + a\, V_2 + V_0$$

$$V_c = a\, V_1 + a^2\, V_2 + V_0$$

Also

$$V_1 = E_1 - Z_1 \frac{I_g}{3}$$

$$V_2 = 0 - Z_2 \frac{I_g}{3}$$

$$V_0 = 0 - Z_0 \frac{I_g}{3}$$

Then with the short circuit applied

$$V_a = 0$$

$$V_b = E_1 \left[a^2 - \frac{a^2\, Z_1 + a\, Z_2 + Z_0}{Z_1 + Z_2 + Z_0} \right]$$

$$= E_1 \left[\frac{\sqrt{3}\, Z_2\, /\overline{90} + \sqrt{3}\, Z_0\, /\overline{150}}{Z_1 + Z_2 + Z_0} \right]$$

$$= \frac{-\, j \sqrt{3} Z_2 - j \dfrac{\sqrt{3}}{2} Z_0 - 1.5 Z_0}{Z_1 + Z_2 + Z_0}$$

in per unit of normal line to neutral volts.

Similarly

$$V_c = E_1 \left[a - \frac{a\, Z_1 + a^2\, Z_2 + Z_0}{Z_1 + Z_2 + Z_0} \right]$$

$$= \frac{+\, j \sqrt{3}\, Z_2 + j \dfrac{\sqrt{3}}{2}\, Z_0 - 1.5\, Z_0}{Z_1 + Z_2 + Z_0}$$ in per unit of normal line to neutral volts.

These values have been calculated neglecting resistance of the lines and transformer for various values of Z_e in per unit of transformer reactance. Figs. 7 and 8 give line to ground volts in per unit of normal line to neutral volts on the open phases as a function of resistance and reactance respectively in the neutral in per unit of transformer reactance.

Appendix XI

DERIVATION OF FORMULA FOR TORQUE OF INDUCTION MOTOR DIRECTLY CONNECTED TO A ROUND ROTOR SYNCHRONOUS MACHINE

Referring to Fig. 1 E is excitation voltage
e is terminal voltage

Then $E_e = \dfrac{x_e}{x_s}\, E$ which is equivalent excitation voltage and

$$x_e = \frac{x_m x_s}{x_m + x_s}$$

For this equivalent circuit the equation for torque is

$$T = \frac{E_e^2 \dfrac{R}{s}}{(x_e + x)^2 + \left(\dfrac{R}{s}\right)^2}$$

(I) Derivation of formula for maximum torque of an induction motor with constant shaft load.

Instability occurs when $\dfrac{d\,T}{d\,s} = 0$ and maximum torque therefore occurs when $\dfrac{R}{S} = x_e + x$ and the current lags E_e by 45 deg. which gives $T_{max} = \dfrac{E_e^2}{2(x_e + x)}$ but it is desirable to express this in terms of terminal voltage which is required to be held constant.

From the vector diagram of this equivalent circuit the in-phase component of current with respect to E_e is

$$\frac{E_e}{2\,(x_e + x)}$$

and

$$e^2 = E_e^2 \left[1 - \frac{x_e}{2\,(x_e + x)} \right]^2 + E_e^2 \left[\frac{x_e}{2\,(x_e + x)} \right]^2$$

from which $$T_{max} = \frac{e^2}{x_e + x + \dfrac{x^2}{x_e + x}}$$

Letting $x = 0.15$; $x_m = 3.0$; $e = 1.0$, the values of maximum torque with constant shaft load as a function of x_s have been calculated and plotted as shown in Fig. 3.

(II) Derivation of formula for critical torque of an induction motor with shaft load varying as $(1 - s)^2$

The critical torque as indicated by point B in Fig. 2 occurs when $\dfrac{d\,T}{d\,s} = \dfrac{d\,L}{d\,s}$ with $L = \dfrac{T\,(1 - s)^2}{(1 - s_c)^2}$ so that

$$\frac{d\,L}{d\,s} = - \frac{2\,T}{(1 - s_c)^2}\,(1 - s) = \frac{-\,2\,T}{(1 - s)} \text{ when } s_c = s$$

but $$T = \frac{\dfrac{R}{s}}{(x_e + x)^2 + (R/s)^2}$$

so that $\dfrac{d\,T}{d\,s}$

$$= \frac{\left[(x_e + x)^2 + \left(\dfrac{R}{s}\right)^2\right]\left(-\dfrac{R}{s^2}\right) - \left(\dfrac{R}{s}\right)\left[-2\dfrac{R^2}{s^3}\right]}{[(x_e + x)^2 + (R/s)^2]^2}$$

which is also equal to $\dfrac{-\,2\dfrac{R}{s\,(1 - s)}}{(x_e + x)^2 + \left(\dfrac{R}{s}\right)^2}$

giving

$$1 - \frac{2\,S}{1 - s} - \frac{2\left(\dfrac{R}{s}\right)^2}{(x + x_e)^2 + (R/s)^2} = 0$$

Solving the above expression for s_c which is the critical slip when $\dfrac{d\,T}{d\,s} = \dfrac{d\,L}{d\,s}$ for values of x_s and the corresponding values of x_e the calculated values of torque with unit terminal voltage are plotted in Fig. 3.

$$\text{using } T_{critical} = \frac{e^2 \dfrac{R}{s_c}}{x^2 + \left(\dfrac{R}{s_c}\right)^2}$$

It must be borne in mind that in the above treatment the terminal voltage e is held constant for steady-state changes in load by adjustment of the generator field rheostat from time to time but that for the transient changes in load under consideration the excitation voltage E or the equivalent E_e remains constant.

Appendix XII

STEP-BY-STEP CALCULATION OF ANGULAR POSITION

Consider any successive time intervals, $n - 2$, $n - \dfrac{3}{2}$, $n - 1$, $n - \dfrac{1}{2}$, n, etc. There will be, using the notation of Part II.

$$\delta_n = \delta_{n-1} + \Delta\,\delta_n$$

$$\Delta\,\delta_n = 360\,f\,\Delta\,t\,S_{n-\frac{1}{2}}$$

$$S_{n-\frac{1}{2}} = S_{n-\frac{3}{2}} + \Delta\,S_{n-1}$$

$$\Delta\,S_{n-1} = \frac{\Delta\,t}{M}\,[T_{n-1} - G_{n-1} - F\,S_{n-1}]$$

from the equation

$$M\,\frac{d\,S}{d\,t} = T - G - F\,S$$

Where T = per unit synchronizing torque
F = per unit damping torque
G = per unit shaft torque

$$S_{n-1} = \frac{S_{n-\frac{3}{2}} + S_{n-\frac{1}{2}}}{2}$$

$$S_{n-\frac{1}{2}} = S_{n-\frac{3}{2}} + \frac{\Delta t}{M}\left[T_{n-1} - G_{n-1} - F\,.\,\frac{S_{n-\frac{3}{2}} + S_{n-\frac{1}{2}}}{2}\right]$$

$$\left(1 + \frac{F\,\Delta t}{2\,M}\right) S_{n-\frac{1}{2}} = \left(1 - \frac{F\,\Delta t}{2\,M}\right) S_{n-\frac{3}{2}} + \frac{\Delta t}{M}\,(T_{n-1} - G_{n-1})$$

if $\frac{F\,\Delta t}{2\,M}$ is small

$$S_{n-\frac{1}{2}} = \left(1 - \frac{F\,\Delta t}{M}\right) S_{n-\frac{3}{2}} + \left(1 - \frac{F\,\Delta t}{2\,M}\right)\frac{\Delta t}{M}\,(T_{n-1} - G_{n-1})$$

$$\Delta\,\delta_n = \left(1 - \frac{F\,\Delta t}{M}\right)\Delta\,\delta_{n-1} + \frac{360\,f\,(\Delta\,t)^2}{M}\left(1 - \frac{F\,\Delta t}{2\,M}\right)(T_{n-1} - G_{n-1})$$

for any interval except the first.

For the first interval

$$S_{n-\frac{1}{2}} = \frac{1}{2}\,\frac{\Delta t}{M}\left(T_{n-1} - G_{n-1} - F\,\frac{S_{n-\frac{1}{2}}}{2}\right)$$

$$S_{n-\frac{1}{2}} = \frac{1}{2}\,\frac{\Delta t}{M}\left(1 - \frac{F\,\Delta t}{4\,M}\right)(T_{n-1} - G_{n-1})$$

$$\Delta\,\delta_n = \frac{360\,f\,(\Delta\,t)^2}{2\,M}\left(1 - \frac{F\,\Delta t}{4\,M}\right)(T_{n-1} - G_{n-1})$$

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18. *Power Limitations of Transmission Systems*, by R. D. Evans and H. K. Sels, A. I. E. E. Trans., Vol. XLIII, 1924, p. 26.

Discussion

L. F. Hunt: Southern California Edison Company has been making stability studies for several years. These studies have given information on what should be done to increase stability.

The first is to prevent flashovers. Some flashovers on the 220-kv. lines, when the lines are loaded, cause interruptions. Therefore very great pains are taken to prevent flashovers.

The second important thing is the clearing of faults. Faults cleared instantly will give little instability. It takes from 0.9 to 1.2 sec. to clear the faults on 220-kv. systems. In all the tests that were made the shortest time was 0.9 sec. to open switches at ends of the line. Most of that time is taken in tripping the oil switches. If oil switches could be made instantaneous instead of taking from 0.4 to 0.5 sec. to open an arc, instability of the system would be materially reduced.

Third, by adding parallel transmission lines, the section that is cut out of the transmission system due to a short circuit is a smaller part of the system; thus the stability will be increased.

Fourth, almost every time the system is out of step it is caused by the generators overspeeding. At one end of the system are the generators and at the other end the load similar to that shown in the paper. Usually the effect of a short circuit is equivalent to adding a very high resistance load to the system. This causes the governors on the system to pick up load. After the fault is cleared the governors are set for a higher load than the load then on the system. Therefore, the machines tend to speed up, causing a greater angular displacement between the sending and the receiving ends, ultimately causing an interruption. This out-of-step condition will be eliminated by slowing down the machines at the generator end at the instant when trouble occurs on the system.

Fifth, quick excitation on synchronous machines will help very materially, because, in case of trouble, it will allow more synchronizing power to pass between the sending end and the receiving end.

R. H. Park: Mr. Hunt has presented a valuable résumé of the results of the stability studies which have been made by the Southern California Edison Company. Of the conclusions presented, the decision in favor of high-speed governing is particularly interesting. Undoubtedly there is every reason for assuming that high-speed actuation of the waterwheel governing mechanism will tend to improve operating condit during disturbances, both by reducing the tendency toward pulling out of step, and also by reducing the time required for again pulling into step after pull-out has occurred.

In addition to Mr. Hunt's written discussion, there has been considerable informal discussion which is not on record. The conclusions arrived at in this informal discussion may be briefly summarized as follows:

a. *Neutral Reactors.* The design of these reactors is necessarily a compromise between the improvement in stability which is obtained, the reduction in relaying current, and the increase in transformer neutral insulation. A preliminary study of these influences has indicated that the reactor may advantageously be designed for voltage under line-to-ground fault conditions of from 60 to 70 per cent of normal leg voltage. This will usually result in a reduction in shock to the system of about 50 per cent for line-to-ground faults and about 30 per cent for two-wire-to-ground faults.

b. *Neutral Resistors.* With neutral resistors, advantage may sometimes be taken of the braking torque, which results with this device due to the heavy power loss which it causes. While such a power loss reduces the shock on the generators, it increases the shock to the system. Therefore, in view of the action of the steam-turbine governors, its use may not do as much good as would be anticipated at first thought. Field data are urgently needed to determine this important point.

c. *Amortisseurs.* Unless neutral reactors are employed, much amortisseur action during the period when a fault is actually on the system cannot be expected, because of the equivalent series impedance introduced by the fault. However, it has been the experience of operating companies that the actual instant of instability may occur some time after the removal of the fault. The amortisseur should have a beneficial action in these cases. On the other hand, the amortisseur unavoidably has the effect of reducing the generators' negative-phase-sequence reactance. This means that it tends to increase the severity of the fault somewhat. For line-to-ground faults this effect is small, but for two-wire-to-ground faults, it is quite appreciable. Therefore, if a preponderance of two-wire-to-ground faults is anticipated, it would appear that the beneficial influences of an amortisseur will be reduced and in fact it might be disadvantageous. The final story as to the value of an amortisseur will only be arrived at after further study and field tests.

d. *Synchronous Condensers.* It would appear that some of our present stability difficulties are the result of the loading up of lines which has been made possible by the increasing use of synchronous condensers, because the condensers permit the attainment of satisfactory voltage conditions at either end of a line with loads much larger than could be employed were no condensers used. Also, apparently there is a further danger attending the use of condensers located remote from generating equipment, as has been borne out by some experiences on the Southern California Edison system. These experiences indicate that when there is a large loss of power in the fault, a considerable fraction of it may be contributed by the condensers, especially if the fault occurs near to them, with the result that they pull out of step and in fact actually slow down to a fraction of normal speed. Thus, the use of intermediate condensers in long lines may be undesirable when heavy power losses are anticipated under fault conditions.

E. H. Bancker: It is believed that some further elaboration of the circle diagram method employed would be desirable. Although this method of calculating torque is strictly applicable only to machines with equal reactance in any axis, it may be used for salient pole machines with correct results if an appropriate reactance and excitation are employed. The reactance to be used is the quadrature synchronous. The excitation is the actual value minus the $i_d (x_d - x_q)$ drop. As the excitation and rotor angles change the fictitious excitation changes. As stated in the paper the variation may be represented by the equation

$$O\,Q = k\,I + k_1 \cos \delta_e + k_2 \sin \delta_e$$

Through oversight, the values of the k terms were not given. They are,

$$k = 1 - \frac{(x_q + x_e)(x_d - x_q)}{r_e^2 + (x_d + x_e)(x_q + x_e)}$$

$$k_1 = \frac{\psi_e (x_q + x_e (x_d - x_q)}{r_e^2 + (x_d + x_e)(x_q + x_e)}$$

$$k_2 = \frac{\psi_e r_e (x_d - x_q)}{r_e^2 + (x_d + x_e)(x_q + x_e)}.$$

Calculation of the Capacitance between Two Wires of a Three-Conductor Cable

BY Y. W. LEE*

Enrolled Student

Synopsis.—This paper develops a formula for calculating the capacitance between two wires of a three-conductor cable. A direct method of calculation is employed, based on the work of Doctor H. B. Dwight. This method gives accurate results independent of empirical or restricted premises.

* * * * *

IN the electrical problems of underground cables, a factor which is very difficult to determine is the "geometric factor" which, as the name implies, involves the dimensions of the cable. The geometric factor is very closely related to the capacitance of the cable; and as a matter of fact, it is a constant times the reciprocal of the capacitance.

In a three-conductor cable, there are nine geometric factors[1, 2], and of course as many capacitances resulting from the different connections of the four elements of the cable, namely, the three conductors and the sheath. The capacitance of the three wires against the sheath, and the capacitance between two wires are the most important ones as the other seven are expressible in terms of them.

Greater accuracy in the determination of the geometric factor is demanded in problems such as the calculations of the dielectric loss, the stress under three-phase voltage, the insulation resistance, the charging current, and so on.

The inverse method of determining the capacitance by first assuming the distribution of the charges, then calculating the equipotential lines, is good only in a few cases where these lines agree with the shapes of the conductors. This method is not applicable to the three-conductor cable. An attempt has been made to correct graphically the lines of flow to secure a more accurate result,[1] but this has not been extended to the case to be considered in this paper. All published formulas relating to the capacitance in a three-conductor cable, with the exception of Professor H. B. Dwight's, are either empirical or restricted.

Professor Dwight of the Massachusetts Institute of Technology presented in the TRANSACTIONS of the A. I. E. E., 1924,[3] a direct method for calculating the capacitance of conductors. The most important case he worked out was the capacitance of the three wires against the sheath in a three-conductor cable. The capacitance between two wires of the cable remained to be determined in order to complete the accurate determination of the geometric factors.

With the valuable assistance of Professor Dwight, the writer has derived a formula for the capacitance between two wires in a three-conductor cable. A check has been made against the experimental curves published by Mr. D. M. Simons.[4] The difference is small, being 3.4 per cent. This calculation was done as thesis work in the Electrical Engineering Department of the Massachusetts Institute of Technology.

METHOD OF CALCULATION

Consider a wire A of radius a and an infinitesimal wire B separated by a distance p. Assume A to carry a charge of Q per unit length, and B to carry $-Q$ per unit length.

From the symmetry of the arrangement, we can assume that the charge density at any point (a, θ) is given by the equation

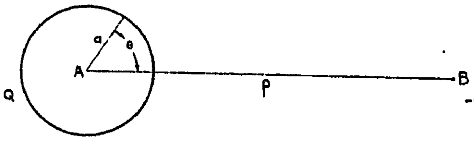

FIG. 1

$$q(\theta) = H_0 + \sum_{n=1}^{n=\infty} H_n \operatorname{Cos} n\,\theta \qquad (1)$$

where H_0 and H_n are constants; and upon their determination, the equation becomes[3]

$$q(\theta) = \frac{Q}{2\,a\,\pi} + \frac{Q}{\pi\,a} \sum_{n=1}^{n=\infty} (a/p)^n \operatorname{Cos} n\,\theta \qquad (2)$$

Evidently, $\frac{Q}{\pi\,a} \sum_{n=1}^{n=\infty} (a/p)^n \operatorname{Cos} n\,\theta$ is the charge density at (a, θ) due to $-Q$ in B.

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[1] *Cable Geometry and the Calculation of Current-Carrying Capacity*, by D. M. Simons, A. I. E. E. TRANS., 1923, p. 600.

[2] "Alternating Currents," by Alex. Russell, Vol. 1, edition of 1914, p. 178.

[3] *The Direct Method of Calculation of Capacitance of Conductors*, by H. B. Dwight, A. I. E. E. TRANS., 1924, p. 958.

[4] "Calculation of the Electrical Problems of Transmission by Underground Cables," by D. M. Simons, *The Electric Journal*, 1925, p. 366.

Now when two wires A and C carrying Q and $-Q$ per unit length respectively are placed close to each other, we can calculate the charge density at any point on either wire by a method of successive approximations.

First, assume that the charges are uniformly distributed over the surfaces of the conductors. By Equation (2), an expression can be set up for the charge density at (a, θ) due to the charge in an element of area on C. Remember that the element of area is the same as the infinitesimal wire B in Fig. 1. To get the charge density at (a, θ) due to the uniformly distributed charge on C, the expression is integrated over the surface of C. Or, mathematically,

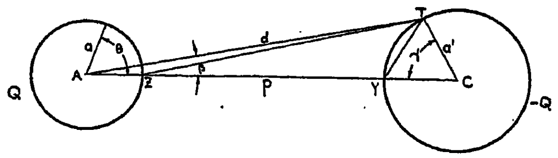

FIG. 2

$$q_1(\theta) = \int_{\gamma=0}^{\gamma=2\pi} \frac{Q\, a'\, d\gamma}{(a\,\pi)\,(2\,a'\,\pi)} \sum_{n=1}^{n=\infty} (a/d)^n \operatorname{Cos} n\,(\theta-\beta) \quad (3)$$

which is integrable since[5,6]

$$\frac{\operatorname{Cos} n\beta}{d^n} = \frac{1}{p^n}\left[1 + \sum_{k=1}^{k=\infty} \frac{(n+k-1)\,!}{(n-1)\,!\,k\,!}\,(a'/p)^k \operatorname{Cos} k\,\gamma\right] \quad (4)$$

and

$$\frac{\operatorname{Sin} n\beta}{d^n} = \frac{1}{p^n} \sum_{k=1}^{k=\infty} \frac{(n+k-1)\,!}{(n-1)\,!\,k\,!}\,(a'/p) \operatorname{Sin} k\,\gamma \quad (5)$$

Other conductors carrying charges can be taken into consideration in the same manner. This is a first approximation, and we shall call $q_1(\theta)$ the first additional charge density. In exactly the same way, $q_1(\gamma)$ can be obtained as the first additional charge density on C, and so on for other conductors that may be present.

In the present problem, there are six conductors to be considered as shown in Fig. 3. A', B', and C' are the images which replace the sheath. A and C' each carries Q per unit length, and C and A' each carries $-Q$ per unit length. B and B' have zero total charge.

A repetition of the process of integration replacing the uniform density by $q_1(\theta)$ and $q_1(\gamma)$ will give $q_2(\theta)$ and $q_2(\gamma)$, the second additional charge densities. When this is done, general expressions for the additional charge densities can be written. The sum of the additional charge densities on one wire and the charge density due to the total charge on itself, is the actual charge density on that wire.

The work done in carrying a unit charge from Z to Y (Fig. 2) against the total charge on C is

$$\int_{\gamma=0}^{\gamma=2\pi} 2\,a'\,q(\gamma) \log (Z\,T/Y\,T)\, d\gamma \quad (6)$$

where $q(\gamma)$ is the total charge density on C. The expression can be integrated because $\log (Z\,T/Y\,T)$ is expressible in terms of γ. For example,[7]

$$\log\left(\frac{Z\,T}{p-a}\right) = -\sum_{k=1}^{k=\infty} (1/k)\left(\frac{a'}{p-a}\right)^k \operatorname{Cos} k\,\gamma \quad (7)$$

Similarly, the work done against all other charges can be evaluated. When the total work is found, the capacitance can be determined immediately since

$$\text{Capacitance} = \frac{Q}{\text{Total work}} \quad (8)$$

THE FORMULA

Let C be the capacitance between any two wires of a three-conductor cable.

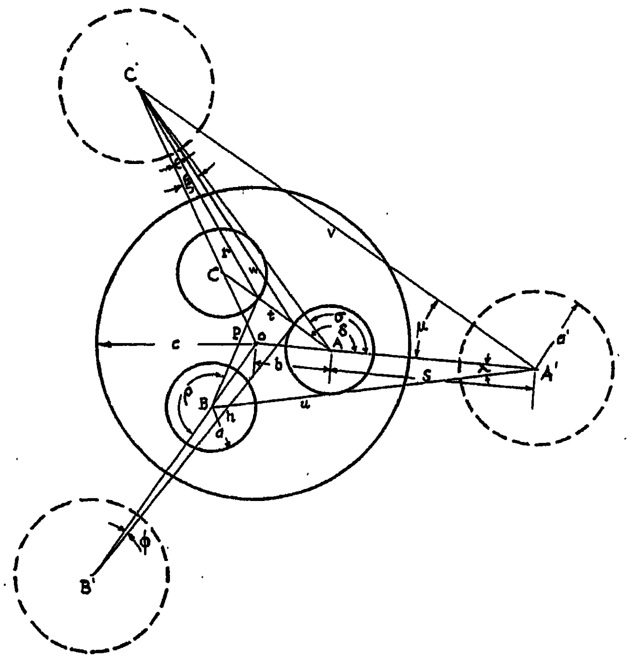

FIG. 3

$$\frac{1}{C} = -4 \sum_{m=1}^{m=\infty} (1/m)\left[\left\{\left(\frac{a}{t-a}\right)^m - 1\right\}\right.$$

$$\{ M_m \operatorname{Cos} m\,\delta + M_m' \operatorname{Sin} m\,\delta \}$$
$$+ (a'/w)^m (N_m \operatorname{Cos} m\,\xi + N_m' \operatorname{Sin} m\,\xi)$$
$$- (a'/r)^m (N_m \operatorname{Cos} m\,\epsilon + N_m' \operatorname{Sin} m\,\epsilon)$$

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[5] "Theory of Infinite Series," by T. J. I'A Bromwich, pp. 158-159.

[6] "An Integration Method of Deriving the A-c. Resistance and Inductance of Conductors," by H. L. Curtis, Scientific Papers No. 374 of the Bureau of Standards, Washington, D. C., Appendix 2.

[7] *Ibid.* Appendix 1.

$$\begin{aligned}&+2(a/p)^m M_m' \,\text{Sin}\, m\,\rho + 2(a'/h)^m N_m' \,\text{Sin}\, m\,\phi \Big] \\ &- 4 \log \left(\frac{a}{t-a} \right) \left(\frac{w}{r} \right).\end{aligned} \tag{9}$$

$$M_m = A_m + B_m + C_m + D_m + \ldots\ldots \tag{10}$$

$$M_m' = A_m' + B_m' + C_m' + D_m' + \ldots\ldots \tag{11}$$

$$N_m = F_m + G_m + H_m + I_m + \ldots\ldots \tag{12}$$

$$N_m' = F_m' + G_m' + H_m' + I_m' + \ldots\ldots \tag{13}$$

$$A_m = (a/s)^m + (a/t)^m \,\text{Cos}\, m\,\delta - (a/u)^m \,\text{Cos}\, m\,\sigma \tag{14}$$

$$A_m' = (a/t)^m \,\text{Sin}\, m\,\delta - (a/u)^m \,\text{Sin}\, m\,\sigma \tag{15}$$

$$\begin{aligned}B_m = \sum_{n=1}^{n=\infty} \frac{(m+n-1)\,!}{(m-1)\,!\,n\,!} \Big[&- (a/s)^m (a'/s)^n F_n \\ &+ (a/t)^{m+n} \{ A_n \,\text{Cos}\, (m-n)\,\delta \\ &- 3\, A_n' \,\text{Sin}\, (m-n)\,\delta \} + (a/u)^m (a'/u)^n \\ &\{ F_n \,\text{Cos}\, (m\,\sigma + n\,\lambda) \\ &+ 3\, F_n' \,\text{Sin}\, (m\,\sigma + n\,\lambda) \} \Big]\end{aligned} \tag{16}$$

$$\begin{aligned}B_m' = \sum_{n=1}^{n=\infty} \frac{(m+n-1)\,!}{(m-1)\,!\,n\,!} \Big[&- (a/s)^m (a'/s)^n F_n' \\ &+ (a/t)^{m+n} \{ A_n \,\text{Sin}\, (m-n)\,\delta \\ &- A_n' \,\text{Cos}\, (m-n)\,\delta \} + (a/u)^m (a'/u)^n \\ &\qquad \{ F^n \,\text{Sin}\, (m\,\sigma + n\,\lambda) \\ &+ F_n' \,\text{Cos}\, (m\,\sigma + n\,\lambda) \} \Big]\end{aligned} \tag{17}$$

$$F_m = - (a'/s)^m + (a'/u)^m \,\text{Cos}\, m\,\lambda - (a'/v)^m \,\text{Cos}\, m\,\mu \tag{18}$$

$$F_m' = (a'/u)^m \,\text{Sin}\, m\,\lambda - (a'/v)^m \,\text{Sin}\, m\,\mu \tag{19}$$

$$\begin{aligned}G_m = \sum_{n=1}^{n=\infty} \frac{(m+n-1)\,!}{(m-1)\,!\,n\,!} \Big[&- (a'/s)^m (a/s)^n A_n \\ &+ (a'/u)^m (a/u)^n \{ A_n \,\text{Cos}\, (m\,\lambda + n\,\sigma) \\ &+ 3\, A_n' \,\text{Sin}\, (m\,\lambda + n\,\sigma) \} + (a'/v)^{m+n} \\ &\{ F_n \,\text{Cos}\, (m-n)\,\mu - 3\, F_n' \,\text{Sin}\, (m-n)\,\mu \} \Big]\end{aligned} \tag{20}$$

$$\begin{aligned}G_m' = \sum_{n=1}^{n=\infty} \frac{(m+n-1)\,!}{(m-1)\,!\,n\,!} \Big[&- (a'/s)^m (a/s)^n A_n' \\ &+ (a'/u)^m (a/u)^n \{ A_n \,\text{Sin}\, (m\,\lambda + n\,\sigma) \\ &+ A_n' \,\text{Cos}\, (m\,\lambda + n\,\sigma) \} + (a'/v^{m+n} \\ &\{ F_n \,\text{Sin}\, (m-n)\,\mu - F_n' \,\text{Cos}\, (m-n)\,\mu \} \Big]\end{aligned} \tag{21}$$

For C_m, C_m', H_m, and H_m', use the expressions for B_m, B_m', G_m, and G_m' respectively, but change A_n, A_n', F_n, and F_n' to B_n, B_n', G_n, and G_n' respectively. A_n, A_n', B_n, B_n', F_n, F_n', G_n, and G_n' are defined by Equations (14), (15), (16), (17), (18), (19), (20), and (21) where m and n are interchanged.

D_m, D_m', I_m, I_m', and the subsequent terms are similarly defined.

For the images,[8]

$$a' = \frac{c^2\,a}{b^2 - a^2} \qquad s + b = \frac{c^2\,b}{b^2 - a^2} \tag{22}$$

$$\delta = 150° \qquad \mu = 30°$$

AN EXAMPLE

The geometric factor G_2 is defined as the geometric factor under three-phase operation.[1] It is related to the capacitance (C) between two wires of a three-conductor cable by the equation

$$G_2 = \frac{3\,k}{4\,C} \tag{23}$$

k is the dielectric coefficient. The letter G_2 for the geometric factor should not be confused with the quantities G_1, G_2, G_3, etc. used throughout this calculation.

Take $a = 1$, $b = \sqrt{3}$, and $c = 2 + \sqrt{3}$. Using Simons' notations,[4] this corresponds to $t/T = 1$, and $(T + t)/d = \frac{1}{2}$. The calculated G_2 is 2.031, and Atkinson's experimental value published by Simons is 2.10. The difference is 3.4 per cent.

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[8] "Elements of the Mathematical Theory of Electricity and Magnetism," by J. J. Thomson, fourth edition, pp. 149 and 176.

Radio Acoustic Position Finding in Hydrography

BY JERRY H. SERVICE*

Associate, A. I. E. E.

Synopsis.—In hydroelectric surveys it is difficult to fix the positions of the soundings when the survey ship is beyond the range of visibility of shore objects; the radio-acoustic method is designed to help in meeting this difficulty. Temporary shore stations are set up, each equipped with a microphone placed in the water in a known position and connected with an amplifier ashore through a cable; the amplifier is in turn connected through a relay to an automatic key driven by clockwork, which causes a radio transmitter to send out a characteristic signal whenever the microphone is disturbed.

When the position of the ship is wanted, a small bomb is fired in the water alongside the ship; the instant of the explosion is automatically recorded on a chronograph aboard the ship. The sound of the explosion disturbs the shore station microphone and the resulting characteristic radio signals of the shore stations are received on board the ship and also recorded on the chronograph. Thus the ship obtains the time of travel of sound in water from her position to each of the shore station microphones, which are in known positions. The speed of sound in sea water being known, the ship's position is thus fixed. The method has been used successfully in the U. S. Coast and Geodetic Survey with the ship 75 mi. or more away from the shore stations.

A device for quick plotting on the field sheet is described. The accuracy of the method is discussed.

INTRODUCTION

In hydrographic surveys, the fundamental objective is the production of accurate nautical charts for the guidance of mariners. Soundings in great number and well distributed over the area surveyed must be taken. These soundings must be accurate as to depth, but it is just as important that the positions of the soundings should be accurately known. That is to say, a survey ship while taking soundings must know her position accurately at all times.

So long as the ship is within the range of visibility of shore objects, natural or artificial, such as mountain peaks, tall chimneys, elevated tanks, prominent lone trees, or specially constructed signals, the problem is comparatively easy in the daytime and in clear weather. At regular short intervals, angles between the right and center, and center and left objects, are simultaneously measured with sextants by two observers on board the ship; these two angles can be set up on a three-arm protractor, or "station pointer," and the ship's position can be plotted within a minute of time.

But at night (except in those rare instances in which three well located lights can be identified), in foggy weather, or when the ship is beyond the range of visibility of shore objects, the problem becomes difficult. Dead reckoning, in which the ship's position is fixed by her distances run (measured by the patent log or the revolution counter) in the directions as given by her compass, with allowances for current and leeway (due to the ship being blown sidewise through the water by the wind), is always open to question. Formerly, when the ship had to stop for every sounding, dead reckoning was especially questionable; now, with the advent of echo sounding, by means of which the ship can run continuously at full speed, dead reckoning is much more satisfactory than it was. Astronomical fixes, even when taken at their best on stars at morning and evening twilight by several observers, have comparatively large probable errors and are limited to a few times per day, and then only when the sky is clear and the horizon is well defined.

If some means could be devised that would locate a survey ship accurately, at frequent intervals, day or night, clear weather or foggy, in rough weather or in smooth, and as far off shore as she might have occasion to work, it may be seen that such a method, if its cost were not excessive, would be very useful.

The British have such a method,[1,2] in which the pressing of a key on board the ship simultaneously detonates a small charge of explosive in the water near the ship and sends out a radio dash. A station on shore records on an Einthoven galvanometer photographic recorder, the time of arrival of the radio dash and also the times of arrival of the sound wave from the explosion at each of a number of hydrophones suitably disposed in known positions on the sea bed. What they get is the distance of the explosion from each hydrophone, and the bearing of the explosion from the mid-point of each pair of hydrophones. The use of the bearing lines in connection with the range lines makes considerable accuracy possible. The shore station transmits the position of the explosion to the ship by radio. Very little equipment is required on board the ship, so that the method is of use in navigation. It is stated that with a 9-oz. charge of explosive, locations can be given within a range of 40 mi. from the hydrophones.

In 1923 the U. S. Coast and Geodetic Survey, in collaboration with the Sound Laboratory of the U. S. Bureau of Standards, worked out a method of locating a survey ship by radio-acoustic methods.[3] While some important practical modifications in details have been made during the past five years, this method is still used with no changes in the general principle. Since 1925 it has been proved economical and successful in the waters off the Pacific Coast of the United States, especially in the waters off Washington and

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1. For all references see Bibliography.

Oregon. In one test run off the coast of Oregon, the Survey Ship *Guide* ran over 200 mi. directly off shore and obtained consistent positions during the entire distance; both the *Guide* and the *Pioneer* have successfully surveyed large areas with the positions of the soundings determined almost exclusively by the radio-acoustic method, the ship being as much as 75 to 80 nautical miles away from the shore station hydrophones during the progress of the work. Thus far, the method has not been used with success in the waters off the Atlantic Coast of the United States, although it has been the subject of experiments off the coasts of North Carolina and Florida.[4]

This American method differs from the British method chiefly in that the working out of position is done on board the ship, the shore station apparatus being essentially automatic so that the shore station personnel is required mainly to keep the equipment in good condition. By this means the ship's position at the instant of explosion becomes known within a very few minutes after the explosion, which is very important in survey work.

Fig. 1—Radio-Acoustic Shore Station

Space does not permit us to trace the development of the American method. The reader can refer to the Publication[3] by Commander Heck, Dr. Eckhardt, and Mr. Keiser for the details of the original apparatus and procedure. The present method has been discussed by Commander W. E. Parker,[5] Chief of the Division of Hydrography and Topography of the Coast and Geodetic Survey, and by the author.[6] It will be treated in its essentials in this paper; a more detailed description can be found in the new Special Publication of the Coast and Geodetic Survey upon the subject, which is now in press.[11]

The Shore Stations

The Survey Ship having a given water area to survey sets up two shore stations, one near each inshore corner of the area. These stations are usually 30 to 40 mi. apart and are often in wild places at a considerable distance from any towns or settlements. Since they will be used at most only a few months, the shelters are of a temporary nature, constructed or set up in one or two days by a party sent ashore from the ship. Fig. 1 shows such a station on San Clemente Island off the coast of California.

The hydrophone, sealed into a watertight, wooden case, filled with sea water, is planted on the sea bottom at a distance varying from a few hundred yards to a mile or more offshore, depending upon the topography of the bottom, the presence or absence of projecting ledges, etc. The hydrophone is a single-button microphone with a rubber case; sometimes two or more hydrophones are used, mounted in the same wooden case and usually connected in parallel. The hydrophone (or set of hydrophones) is connected to the shore station through a single-conductor cable and the sea water ground.

The wooden case into which the hydrophone is sealed may be a keg or a specially constructed box of about the size of a keg. It was introduced by the writer as the result of a study of a paper by Brillié,[7] after a series of experiments by the writer and Chief Wireless Operator A. M. Vincent, of the Survey Ship *Guide*. These experiments showed that the wooden case passes sound from the explosion without appreciable attenuation, but eliminates a great many very troublesome strays that are probably due to the mechanical action of the water, bits of sand, shells, etc., upon the hydrophone.

The cable was designed by Lieutenant Commander Thomas J. Maher, U. S. Coast and Geodetic Survey, and the author, and consists of 19-strand tinned aircraft cable 1/8 in. in diameter) insulated with a 1/8-in. belt of 40 per cent to 60 per cent rubber. This cable has great tensile strength, its insulation resistance remains high after long immersion in sea water, and the insulation is very resistant to abrasion. The high electrical resistance of this cable is not a serious disadvantage. The cable is specially manufactured for the Survey. In some localities, as on rocky beaches, single-conductor deep-sea cable is used through the breakers. Usually it is found satisfactory to run the lighter cable through 3/4-in. pipe from a point inside high-water line to a point outside low water line; for protection of the cable, the pipe is fitted with a fiber or wooden bushing and a piece of rubber hose at each end.

The essentials of the shore station equipment except for batteries, are shown schematically in Fig. 2. When the sound from the distant explosion reaches the hydrophone its resistance changes and an electrical impulse passes through the input winding of the first transformer of the amplifier. This impulse, amplified, passes through the line circuit of the commercial standard telegraph relay and as a result the local circuit of that relay is momentarily closed. The closing of the local circuit of the relay has two effects: (1) the radio sending key is short-circuited by the relay contacts and a dash is broadcasted by the station with a scarcely appreciable lag behind the arrival of the sound from the explosion at the hydrophone; and (2) the automatic key is set into operation, which is driven by clockwork, and by means of a notched wheel causes the radio transmitter to broadcast the characteristic signal of the station, which may be three long dashes, or a dot and two dashes, or whatever signal may be desired.

There is nothing of special interest connected with the amplifier. The input impedance of the first transformer is matched approximately to the impedance of the hydrophone and cable. The line circuit impedance of the relay is matched to the output impedance of the last tube of the amplifier. Usually, radiotrons UX201A are used in the first two stages, and a UX112 in the third stage. Suitable values for plate and grid potentials have been found by experiment.

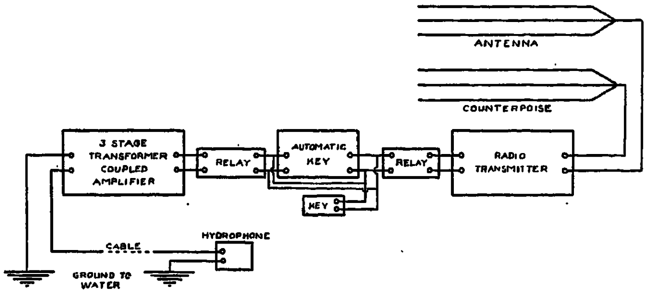

FIG. 2—ESSENTIALS OF RADIO-ACOUSTIC SHORE STATION APPARATUS—U. S. COAST AND GEODETIC SURVEY

The automatic key is that described by Heck, Eckhardt, and Keiser.[3] It consists of a pair of contacts connected in parallel with the radio sending key. These contacts are normally held open by a wiper resting upon the periphery of a notched wheel. This wheel is driven by a clockwork mechanism set in motion whenever the relay local circuit is closed; a device that stops the clockwork automatically when the wheel has made exactly one revolution is included.

The relay shown alongside the sending key is merely a pony telegraph relay included to insulate the sending key and the automatic key from the high plate potential of the transmitter; the transmitter is keyed in the plate circuit.

There is nothing particularly remarkable about the radio transmitter. It is simply a Hartley oscillator using two UX210 radiotron tubes in parallel and operating at 140 meters wavelength. Both stations operating in connection with a given ship must keep their transmitters adjusted to approximately the same frequency.

THE SHIP INSTALLATION

The essentials of the ship installation, exclusive of batteries, are shown schematically in Fig. 3. The hydrophone is mounted well below the water line in a tank of water in contact with the outer plating of the ship.

The amplifier preferably has the first transformer that is connected with the hydrophone distinct from the first transformer that is connected with the output of the radio receiver, in order that the transformer input impedances may be properly matched to the impedances of the circuits into which they are connected. Usually, two or three stages of amplification are sufficient either for the incoming radio signals or for the hydrophone circuit impulses.

The chronograph drives a ¾-in. tape at the rate of about one inch per second. The drive was modified by the author and consists of a 12-volt shunt motor driven by a 12-volt storage battery of large capacity; by this arrangement satisfactory speed regulation is obtained without a governor. The pen magnet winding that is connected with the amplifier has its impedance approximately matched to the output impedance of the last tube of the amplifier.

EXPLOSIVE CHARGES

The explosive charge is detonated by a fulminate blasting cap into which a short length of waterproof fuse is fitted. If the ship is within 15 or 20 mi. of each of the two stations, one of these blasting caps will usually send sound energy of sufficient amplitude to the hydrophones at both station to actuate the station apparatus. Beyond the range of a blasting cap, a friction top, pint-size, tin can filled with TNT into which the blasting cap is imbedded is usually sufficient. For the greatest distances, a bomb designed by the author is used. This bomb consists of a hollow cast iron sphere of 5-in. inside diameter and ½-in. wall thickness, filled with TNT; the blasting cap and fuse (as well as the TNT) are introduced through a small opening; the blasting cap is imbedded in the TNT at the center of the sphere. In these cast iron bombs, as well as in the tin can bombs, the fuse opening is sealed with soft pitch or some similar material after the fuse is in place.

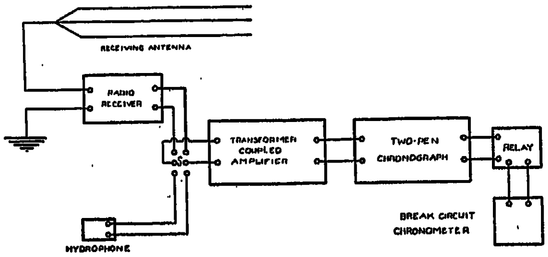

FIG. 3—ESSENTIALS OF RADIO-ACOUSTIC SHIP APPARATUS —U. S. COAST AND GEODETIC SURVEY

OPERATION OF THE SYSTEM

When a position is wanted, the switch *S*, (Fig. 3) is thrown to the hydrophone, the chronograph is started, the pens are seen to be functioning with the time pen making the second marks, and a bomb is ignited (by touching the end of the fuse to a hot wire) and thrown overboard. The ship need not modify either her course or speed for this procedure. The instant of explosion is recorded on the chronograph by means of the ship's hydrophone, the amplifier, and the amplifier pen magnet. The switch S, (Fig. 3) is then thrown to the ship's radio receiver.

The sound energy flows out from the explosion and, after intervals, reaches the hydrophones at the two stations. When this sound reaches the hydrophone at a given station, that station, with scarcely appreciable lag, broadcasts a radio dash, identified immediately afterward by the characteristic signal of the station. Dash and signal are received by the ship and recorded on the chronograph tape. The time of travel of the radio dash from station to ship is negligible. Instrumental lags can be determined at the beginning of the season and then checked from time to time.

From the chronograph tape, the time of travel of sound energy from the explosion to the hydrophone at each station can be read off quickly to within one or two one-hundredths of a second. The positions of the station hydrophones have been located accurately and plotted upon the survey sheet when the hydrophones were planted.

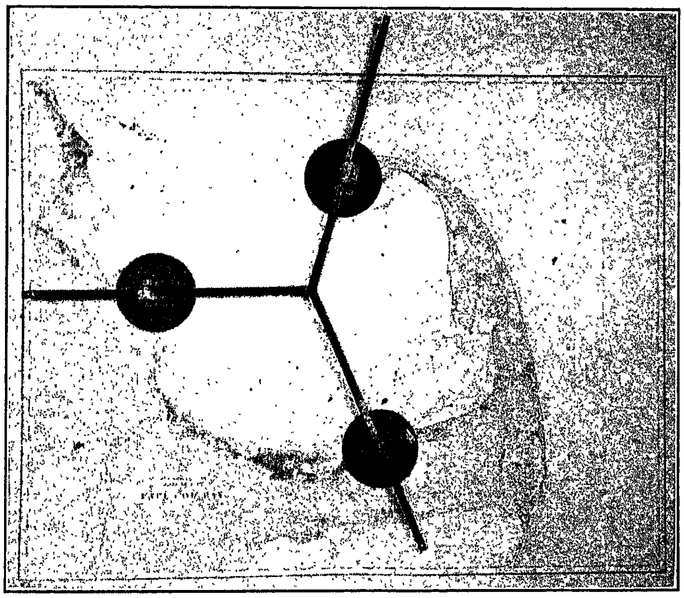

Fig. 4—Parkhurst—Service Radio-Acoustic Plotter

Speed of Sound in Sea Water

Since the distance from the explosion to the hydrophone at each station is required, in addition to the time of travel of sound energy to each station the speed of sound in sea water must be known. This speed is a function of the mean (from surface to bottom and over the range) temperature, pressure, and salinity of the water. From studies made within the past few years the speed of sound in sea water is quite well known under all conditions of temperature, pressure, and salinity likely to be encountered.[4, 8, 9] Also, the temperature and salinity conditions are determined during the season in order that correct sound speeds may be known for echo soundings. Hence, it may be assumed that the correct speed of sound for computing radio-acoustic ranges will be available.

Plotting the Positions

Since the positions of the station hydrophones are known and have been plotted upon the survey sheet, and the distances from the explosion to each hydrophone have been determined by the radio acoustic method, the problem is to find (upon the survey sheet) the vertex of a triangle when the base and the lengths of the other two sides are known. This problem would be easy of solution were it not for the distortion of the survey sheet and the necessity for economy of time. In the plotting of the final "smooth sheet," corrections must be made for distortion, and speed is not so essential; in the plotting of the preliminary work sheet or "boat sheet," distortion may usually be disregarded and speed is quite important.

For plotting on the boat sheet where distortion of the sheet may be disregarded, the plotting device designed by Douglas L. Parkhurst, Chief of Division of Instruments of the Coast Geodetic Survey, and the author, can be used to advantage. This plotting device is shown in Fig. 4, and consists of a pair of arms pivoted at a pricking device; with zero at the pivot, graduations are marked on the arms which represent the distances (on the scale of the hydrographic sheet) that sound will travel in the number of seconds represented by the graduation marks; of course, a mean value of the speed of sound in sea water must be used in laying out the graduations on these arms. An index head is tacked to the chart table through the survey sheet over the plotted position of each hydrophone. The arms slide in grooves on these index heads. Suppose then, that it is found that sound travels from the ship to hydrophone A in 44.82 seconds, and to hydrophone B in 39.19 seconds. The arm in the index head that is over the plotted position of A is moved in or out until graduation 44 is opposite 0.82 on the index head, and then clamped; likewise 39.19 is set up on the arm that slides in the index head at B. The pricker will then be over the position of the ship on the sheet, and the position can be pricked.

Three arms and three index heads are provided, but usually only two are used because there are generally but two stations.

Accuracy of the Method

The accuracy of the method is limited by the accuracy with which the speed of sound is known and by the angle at which the two distance lines intersect. If the physical conditions of the water are fairly well known, the speed, and therefore the two distances, will have an uncertainty not greater than 0.5 of 1 per cent, probably no greater than 0.3 of 1 per cent. That is to say, if the ship is about 50 mi. from the two hydrophones, she can determine her position from either with an uncertainty of the order of 300 meters. Then, of course, the accuracy of her position, determined from the two distances, will depend upon the angle of intersection of the two arcs about the respective hydrophones as centers.

Captain L. Tonta, Director of the International Hydrographic Bureau, has proposed[10] a rather brief method of computation of radio-acoustic positions that may prove of advantage for final plotting on the smooth sheets. This method eliminates error of position due to a small error in the value assumed for the speed of sound. The reader is referred to Captain Tonta's original paper for the details of this method.

In conclusion, the author wishes to express his appreciation to those of his superior officers and associates in the Coast and Geodetic Survey who have helped him in the preparation of this paper, and to C. L. Terrel, of the class of 1928 at the Ohio State University, who inked and lettered the diagrams.

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Economies in Central Power Service
as Illustrated by the Duke Power System

BY W. S. LEE[1]
Fellow, A. I. E. E.

Synopsis.—This paper invites the attention of the engineering profession to the advantages and economies which may be obtained by coordinating both hydro and steam power stations of various kinds, and electric transmission and distribution lines serving a large industrial territory in a unified and centrally controlled system. For illustration, a general description of the generating and distribution system of the Duke Power Company, operating in the Piedmont section of the Carolinas, is given.

EVERYONE who studies the statistics on electric power output in the United States will be amazed at the rapid growth of the electrical industry during the past decade and how, by the construction of larger and larger commercial electrical central stations and the merging of existing electrical properties, the increasing demand for electricity for lighting, power, and transportation was met.

Through this centralization, it was made possible to give uniform and dependable service to the customer, to maintain the same rates, and even lower them to domestic consumers in the face of increasing costs of labor and materials, to make the investments in properties of such character safe and attractive, to afford the support of an organization highly trained in the efficient planning, constructing, operating, and improving of utility systems, to make purchases in large quantities and to engage aggressively in building-up the electric light and power business. Other advantages are the grouping of hydro and steam power stations of various kinds to permit the full and economical utilization of the available natural resources of power.

The large generating plants deliver the electric energy to trunk transmission lines which feed the distributing systems of cities and towns and furnish power to the lines at industrial centers. In addition, interconnections of trunk lines of the transmission systems of large independent power companies operating in adjoining territories provide means for marketing wholesale power blocks from one utility to another, for interchange of power between systems and, in case of emergency, for stand-by service.

Due to their higher plant efficiencies and the lowering of construction costs, the number of large steam electric generating stations is rapidly increasing and water-powers of large size, which were considered uneconomical on account of the inability of marketing such large blocks of power within a reasonable period of time by local utilities, are being developed. Industrial plants abandon operation of their old inefficient power stations, and wasteful generating stations of small suburban electric properties are being shut down. An increasing number of manufacturing plants is being located away from the large centers of population, this trend towards decentralization being made possible by reason of the fact that high-tension transmission lines can be tapped at suitable locations away from metropolitan areas. Old inefficient water-power plants are being overhauled and existing hydro stations utilizing only a portion of the available water-power of the stream are being rebuilt and enlarged so as to lower the cost of the electric power generated.

A striking example showing the development of a local concern organized for the sale of electricity generated at a single water-power plant about 23 years ago to one of the largest central stations generating and distributing systems in the world is given by the Duke Power Company operating in the Piedmont section of the Carolinas. This company is now operating a number of hydro and steam electric plants having an aggregate installed capacity of 873,895 kv-a., and the power is fed into a transmission and distribution system consisting of approximately 4000 mi. of circuits, of which about 50 per cent are 100,000-volt steel tower lines. One hundred and sixty thriving industrial communities and many isolated cotton mills and factories are served by these lines, and in 1927 the total power generated and purchased by the Duke Power System amounted to 1,745,776,428 kw-hr. This compares with an average output of 19,000,000 kw-hr. of the old Catawba Station, which was the first plant operated and which was redesigned and reconstructed in 1925.

The generating system of the Duke Power Company may be subdivided into the following groups:

1. Hydro stations which use the fall and run of the river.
2. Hydro stations which use the fall and run of the river plus a small amount of storage taking care of the night and Sunday flow and, perhaps, of minor weekly fluctuations of the flow of the river.
3. Hydro stations which have a large storage capacity behind them and which are used as a valve, or outlet, to supply the deficiency in power of other stations during low-water seasons.
4. Steam plants designed to operate intermittently and during low-water periods, termed "stand-by plants."
5. Steam plants designed to operate twelve months of the year and capable of supplying a constant amount of power, termed "base plants."

Of special interest are the twelve hydro stations

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located on the Catawba River the flow of which is almost completely regulated so that all these stations may be classed under Group 3. Beginning with the power plant farthest upstream, the names and installed capacities of these stations are as follows:

Name of hydro station on Catawba River	Rated capacity of station kv-a.
Bridgewater	25,000
Rhodhiss	21,875
Oxford	45,000
Lookout Shoals	23,400
Mountain Island	75,000
Catawba	75,000
Fishing Creek	37,500
Great Falls	30,000
Dearborn	56,250
Rocky Creek	30,000
Cedar Creek	56,250
Wateree	70,000
Total	555,275

The Bridgewater, Rhodhiss, and Oxford Stations, located in the upper region of the Catawba River, and the Catawba Station, located below the junction of the South Fork of the Catawba River, have large storage reservoirs behind them for the retention of the flood-waters and excess flow of the river.

The aggregate installed capacity of the six steam power plants is 244,313 kv-a., of which the Buck Station, using powdered fuel and having a rated capacity of 87,500 kv-a., is to be classed under Group 5. It should be added that the Duke Power Company now has under construction a large powdered fuel steam power station on the Catawba River near the Mountain Island hydro station, where an ample supply of condensing water is available. This station is located closest to the center of gravity of the entire load system and the initial installation will consist of two 60,000-kw. units, whereas the plans call for an ultimate installation of 480,000 kw.

The hydro stations to be classed under Groups 1 and 2 are operated in conjunction with the stand-by steam plants under Group 4, which arrangement will permit the most effective utilization of the stream flow under the conditions. The locations and rated capacities of these stations are as follows:

Name of hydro station	Name of river	Rated capacity of station kv-a.
Gaston Shoals	Broad	12,750
99 Island	Broad	22,500
Tuxedo	Green	6,250
Turner	Green	6,880
Portman Shoals	Seneca	9,500
Gregg Shoals	Savannah	2,250
Lake Lure	Rocky Broad	4,500
Saluda	Saluda	2,600
Idols	Yadkin	1,000
Plants of less than 1000 kv-a. capacity		6,077
Total		74,307

The steam power plants are located at strategical points of the system; combining Groups 4 and 5, they are:

Name of steam station	Rated capacity of station kv-a.
Buck	87,500
Eno	31,250
Greensboro	8,000
Greenville	8,000
Mount Holly	45,500
Tiger	37,500
Stations leased	26,563
Total	244,313

A summary giving the generating capacity of the Duke Power System, arranged by groups, discloses the following interesting facts:

Number of group	Total rated capacity of stations kv-a.	Per cent of total capacity of entire system
Hydro No. 1	7,777	0.89
Hydro No. 2	66,530	7.61
Hydro No. 3	555,275	63.54
Steam No. 4	156,813	17.95
Steam No. 5	87,500	10.01
All groups	873,895	100.00

If the steam power station of 150,000 kv-a. initial capacity now under construction is included, the ratio of steam to total generating capacity of the system will be increased from 27.96 per cent to 38.51 per cent.

To give an outline of the transmission and distribution system of the Duke Power Company, 100,000-volt double-circuit feeder lines from points of concentration of power generation tap the 100,000-volt double-circuit trunk lines running through the load centers of the Piedmont Section of the Carolinas. At these centers, the current is stepped down to 44,000 volts and delivered to the distribution system. The object of using the lower voltage is to reduce the cost of the substations serving the large power customers and public utility branches of the company; and wherever feasible, a generating station is tied-in directly to the 44,000-volt system to avoid double transformation.

At present approximately the following lines are in operation:

Voltage of circuit	Approximate length of circuit miles
100,000	2000
44,000	1900
13,200	100

The standard secondary delivery voltages are 575 and 2300.

Interconnection of the Duke Power Company's trunk lines is made for delivery of large blocks of power to it at the High Rock Station on the Yadkin River of the Tallassee Power Company, and a line is contemplated for connection with the hydro plant of the Lexington Water Power Company, now under construction on the Saluda River near Columbia, S. C. Interconnections for interchange of power and stand-by service are made with the trunk lines of the South-Eastern Power Company and the Carolina Power & Light Company.

In the process of development of the Duke Power Company effort was made to maintain the entire system in good operating condition and to obtain the best results by making improvements on existing plants wherever necessary, even to the extent of abandoning old plants in the interest of fuller and more efficient utilization of the properties. This latter policy was followed up with the fullest success in the case of the old Catawba Station representing an investment of more than one million dollars.

As already mentioned, this hydro plant containing eight rope-driven generators of a total capacity of 8000 kv-a. was built 23 years ago. The normal head at this station was 23 ft. and the over-all efficiency of the plant was about 70 per cent. The storage capacity of the pond was practically negligible and to obtain the benefit of the night and Sunday flow, the plant had to be operated continuously. Furthermore, the available uniform flow at this station was considerably augmented due to the regulating effect of the large storage reservoirs, since built on the Upper Catawba River. The question therefore arose whether additional machinery should be installed and the old plant overhauled or the dam be raised so that the water would back to the tail-race of the company's Mountain Island Station, 25 mi. further upstream, thus creating another large storage reservoir, and the building of an entirely new power house. By the adoption of this latter scheme, not only a reservoir of approximately ten billion cubic feet available storage capacity was created, making an additional regulated flow available at the existing stations on the lower Catawba River with a combined head of 250 ft., but the installation of the new power station could be increased from 8000 kv-a. of the old station to 75,000 kv-a. due to the higher head of 70 ft. and full utilization of the regulated stream flow.

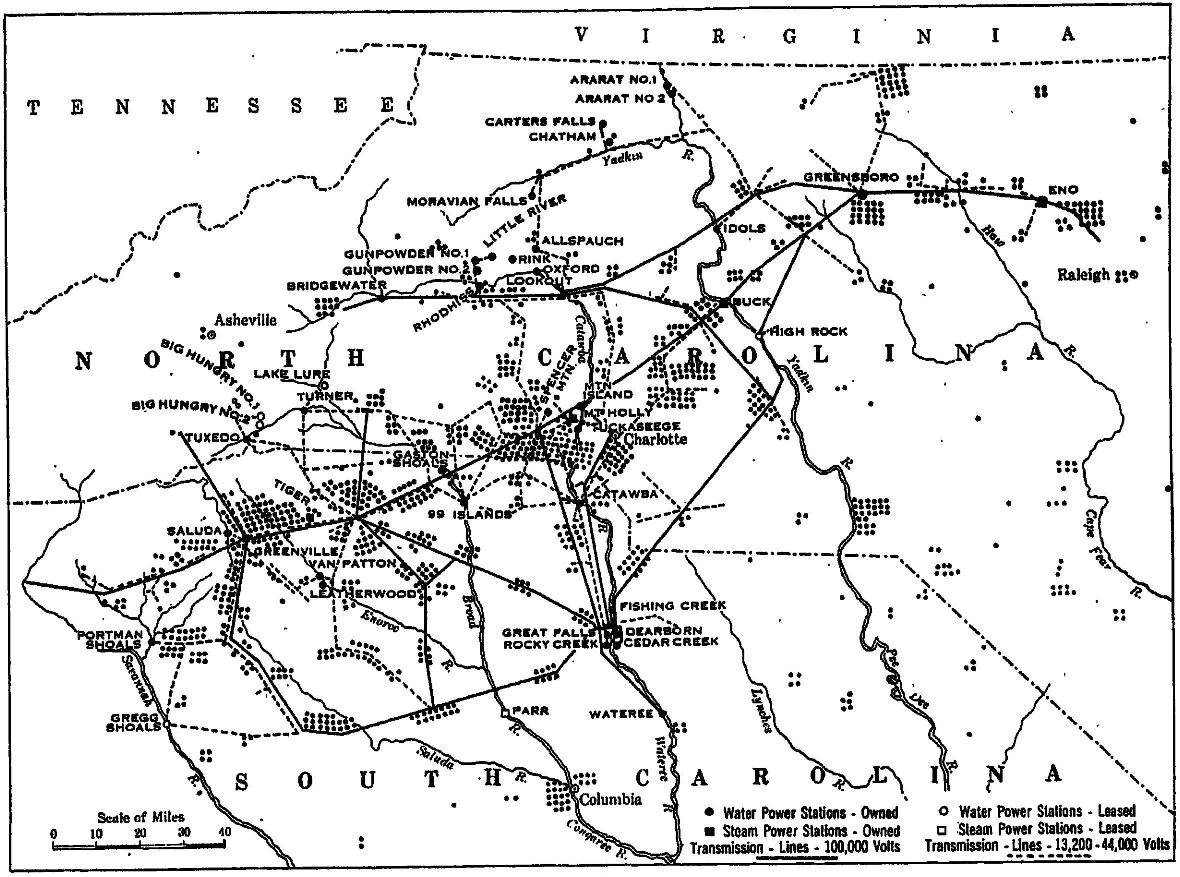

Fig. 1

The map in Fig. 1 shows the outline of the states of North and South Carolina. There is shown by dots, each 10,000 spindles located within these two states. It will readily be noted that the industrial expansion follows the transmission lines of a central system.

Notwithstanding the great industrial development in the Carolinas during the last ten years, the prospects for further growth of the electric light and power business are very bright. The demand for power and light in the home, on the farm, and in industries is increasing steadily and new fields are being opened up constantly.

In anticipation of this ever increasing demand for electric energy, the Duke Power Company is going ahead with a definite program of extensions and improvements to its system to meet future service requirements.

Discussion

For discussion of this paper see page 212.

Southeastern Power & Light System
Interesting Features of Development and Operation

A. T. HUTCHINS*
Non-Member

Synopsis.—*The rapid growth of the Southeastern Power & Light system is noted. The long forecast of system load which has been made together with some other features of development are presented briefly. A short discussion of the routine of operating methods and importance of load dispatching together with interesting features of a new steam unit of 60,000-kw. capacity, and interesting features of design for a hydro plant at Jordan Dam rapidly nearing completion are included.*

LARGE interconnected groups of public service units are receiving a great deal of attention at this time. The growth of the systems here in the Southeastern Section has been discussed at some length in a number of articles which have appeared during the past several months, so that it is impossible to discuss such problems without some repetition. Some of the articles have gone into detail in discussing important features of design and operation. We shall attempt to point out briefly a number of features which we think may be of interest.

Among the larger groups of public utilities, the Southeastern Power & Light Company is scarcely more than an infant. Organized in 1924, the last important changes in its structure were made only a few months past. The generation reported for 1925, 1926, and 1927 were approximately 1.2, 2.0, and 2.2 billion kw-hr. The increase in 1926 over 1925 was largely due to the addition of the Georgia companies.

ADVANTAGES FROM INTERCONNECTION

During its short life there have been realized for its subsidiaries many important benefits from physical interconnection and coordinated load dispatching. Improvement in economy of operation has been secured, first, by carrying the load of small communities over lines from sources of low cost of generation, and second, by coordinated use of hydro plants of the storage and run-of-river type and of steam plants, and by construction of new plants in units of large capacity. Improved service has been secured through better interconnections and increased number of sources of power. The accompanying map, Fig. 1, shows the main transmission lines connecting the larger loads with the principal generating plants. The advantage to the load districts resulting from service from a number of lines from different directions is easily appreciated when it is noted that severe meteorological disturbances do not often occur simultaneously over a wide area. Usually only a narrow zone is affected by wind storms of such severity as to disable a circuit so that it cannot be reclosed after tripping. Similarly storms accompanied by severe lightning usually travel over the country so that these disturbances are not simultaneous over wide areas. In general, the larger loads are supplied by lines and plants of such capacity that service is maintained even if more than one line is out of service. These facts explain the great improvement secured by building lines supplying the same area along routes separated from each other.

SYSTEM PLANNING

Extensive surveys of load prospects in every section of the territory have been projected several years into the future. Although it is known that the best of such estimates will miss the final development, some very important features are well defined. The location of important water power sites is known, the extent of coal fields and coal qualities is fairly well known, and the major trunk lines for the system have already been built. With this foundation, a study of load densities for the various sections of the system, extending ten or twelve years into the future, are of value principally to prevent any construction which would not fit with good economy into the final set-up. This being secured, the

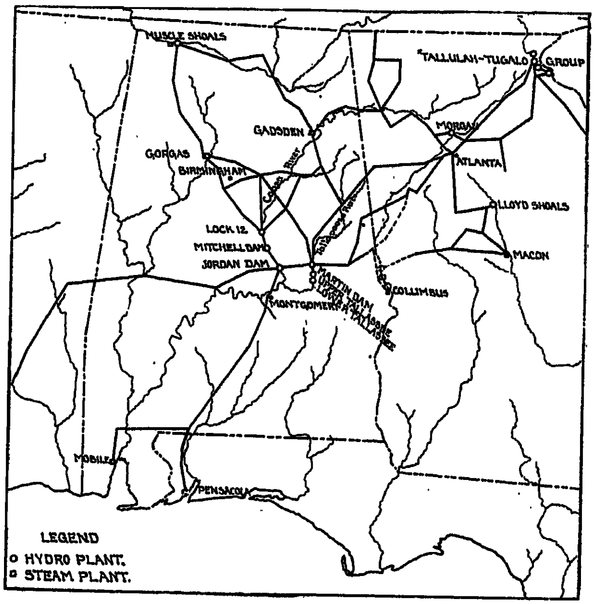

FIG. 1—PRINCIPAL LINES AND PLANTS OF THE SOUTHEASTERN POWER & LIGHT COMPANY'S SYSTEM

procedure resolves itself into making definite plans to care for load conditions two years in advance.

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*Superintendent of Production, Alabama Power Company, Birmingham, Ala.

Presented at the Regional Meeting of the Southern District No. 4 of the A. I. E. E.

HYDRO PLANTS

Engineers are familiar with the usual method of the evaluation of a stream at a point under consideration as a site of a hydroelectric plant using the entire history of stream flow, the power-per cent-time curves for the stream, and an estimate of the cost of construction, including transmission lines to the load.

More engineering judgment is required for the evaluation of local conditions, such items as foundations, protection for abutments in earth banks, and protection of downstream surface exposed to erosion by water spilled at high heads. We will discuss some details of design a little later.

In general, the hydraulic structures being built for this system have a relatively high factor of safety, due first to the point of view of the engineers, and, no doubt, partly to the comparatively short history of stream flows resulting in a greater uncertainty as to maximum flow to be expected.

Although most of the hydro plants follow conventional lines there is an occasional plant whose design includes features of interest.

The design of Jordan Dam which is located about 18 mi. down stream from Mitchell Dam on the Coosa River makes use of a variation in forebay level and the buttress type of power house which may be of interest.

Descriptions of the Thurlow back-water suppressor installed at Mitchell Dam have been published* and these will not be repeated here. It is only necessary to note that the use of the suppressor will maintain normal head on the plant with flows up to 170,000 cu. ft. per sec. at which flow the tail race is up about 15 ft.

The design at Jordan Dam takes advantage of this feature and raises the forebay level 7 ft. to compensate for tail-race rises at high flows.

The normal tail-race level at Mitchell Dam is at elevation 282 to 283. The spillway at Jordan is 1122 ft. long with 612 ft. open at elevation 283. The remainder is controlled by 17 gates whose crest is at elevation 290, each gate being 30 ft. long and 18 ft. deep.

With a stream flow of 52,000 cu. ft. per sec. approximately 17,000 cu. ft. per sec. may be used through the four 36,000-hp. wheels and 35,000 cu. ft. per sec. will flow through the open spillway section bringing the forebay level to the elevation 290 and actually increasing the head on the plant. It is expected that this seven-foot rise in the forebay level will compensate for the tail race rise up to stream flows of 75,000 cu. ft. per sec.

It is apparent that while 283 is the elevation for the tail race at Mitchell Dam and also the open spillway at Jordan, the backwater suppressor at Mitchell Dam will maintain full head against the rise of seven feet.

In addition to this the open spillway avoids the necessity for operating spillway gates except for flows above 52,000 cu. ft. per sec.

A general idea of the buttress type power house is shown in Fig. 5. At each end of the building and between units, buttresses extend from the upstream face of the powerhouse to the solid masonry between draft tubes, thus carrying the greater part of the load on this section of the dam. Such design permits the location of units 40 ft. nearer the face of the dam, and shortens the penstocks by that distance.

STEAM PLANTS

The position of new steam plants in the load diagram and the determination of the use factor will define the relation of increased investment, increased efficiency, and the resulting over-all economy with a known fuel cost.

The use of either 600-lb. or 1200-lb. pressure of steam with reheat cycles and the combined cycle of mercury vapor and steam has had wide publicity and plants using these cycles are increasing in number with a possible trend to neglect 600-lb. pressure and step from 400-lb. to 800-lb. or 1200-lb. pressure.

The most recent unit under construction on this system is designed to use 400-lb. pressure at the turbine throttle, a steam temperature of 725 deg. fahr., and a net economy of the plant for a year's output of approximately 16,000 B. t. u. per kw-hr. On account of high temperatures of circulating water at Gorgas, this unit was designed for best efficiency with 2-in. back pressure at the exhaust nozzle. Some of the essential features of this unit are as follows:

Turbo generator—60,000-kw., 90 power factor, 13,800-volt, single-shaft, 1800-rev. per min., closed generator cooling system using raw water for cooling.

Turbine—three valves 17-stage with 4 bleed points for heating the feed water to 360 deg. fahr. at 52,000 kw. load and a B. t. u. rate chargeable to the turbine—11,350 B. t. u. per kw-hr. at that load.

The unit is built for a maximum load of 66,667 kw. at unity power factor. Steam will be supplied to this turbine from two boilers, each rated at 3040 hp. and equipped with pulverized fuel burners and fans of sufficient capacity to secure a maximum rating of 450,000 lb. per hr. With each boiler there is installed a plate type air preheater of 30,600 sq. ft. and fin type side and rear walls with 3050 sq. ft. of surface. Each boiler is equipped with eight cylindrical burners for horizontal firing and has a furnace with cubical contents of 24,000 cu. ft. so that there will be a release of 18,000 B. t. u. per cu. ft. per hr. at normal rating, this being approximately 350,000 lb. of steam per boiler per hr. and the specified efficiency of boiler unit and furnace at that output is 83.7 per cent.

The two boilers will be supplied with pulverized coal through a central system from three 15-ton Raymond mills having 6 rolls each. These are arranged for mill

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*"New Developments in Hydroelectric Power Plant Designs," by J. A. Sirnit, Amer. Soc. Mech. Eng. *Trans.*, Vol. 44, p. 361-'22.

drying and the air exhaust from the system with the fines not thrown down in the cyclones goes directly to the furnace. This provides a system as free from escaping dust as is possible to secure. In fact, a great deal of attention to design is given to securing freedom from dust in all parts of the plant.

It may be interesting to note the reason for some of these features of design.

The unit arrangement is followed without spares, capacity at the hydro plants being available in case of a drop in load on any steam plant unit. The use of 400-lb. pressure at the throttle results in maximum drum pressure of 475-lb. gage, and this necessitated the use of 600-lb. valves and fittings. It was found that the increased capacity of the turbine and slight increase in efficiency more than compensated for the added cost of valves and fittings designed for 600-lb. pressure over those for 400-lb. pressure.

The use of air preheaters and a correspondingly high temperature of gases leaving the boiler surface with the high pressure used showed good economy in the use of the fourth bleed point for feed water heating. However, on account of crowding of piping and heaters and consequent difficulty in operation and maintenance, it is likely that the next unit will use only three bleed points for feed-water heating.

LINES AND TIE-IN FACILITIES

Lines are always designed for economy based on load and use factor but the necessity for carrying loads with one or more circuits out results in a system which is more or less flexible and which, under certain conditions, makes a maximum use of regulating equipment such as synchronous condensers or spare generators operated as condensers.

The conditions where design based on pure engineering warrants the use of higher voltages for transmission, high-speed excitation of generators, synchronous condensers, and tap changing transformers are receiving a great deal of attention from writers for the technical and trade press and will not be discussed here.

At this time 125-kv-a. capacity in synchronous condensers are installed at advantageous points on the system. One of these having a capacity of 15,000 kv-a., located at Lindale, Georgia, is equipped with a high-speed excitation system. A 90-mi. line from the U. S. Government plants on the Tennessee River to Gorgas, near Birmingham, has been in operation at 154 kv. for some time. A 133-mi. line from Martin Dam to the Atlanta district is spaced and insulated for the same voltage. Three of the newer hydro plants, the last of which will not be in service until next year, were designed for high speed excitation.

A capacity of 110,000 kv-a. in tap changing transformers for regulating voltage while carrying load are in use or purchased for installation at three of the generating plants. This location at the generating plants was determined by the fact that these particular plants are required by the allocation of load to operate part time as a generating plant and part time as substations.

In a system so extensive and having generating plants using stream flow varying so greatly from season to season or over a cycle of years the securing of high load factors on transmission lines is extremely difficult and increased losses, due to overloading under unusual conditions, must be accepted in place of the cost of additional copper and a lower use factor.

The combination of run-of-river and storage plants, served by the same lines, is, in general, advantageous, but extreme conditions arise under which it is not practicable to transmit with normal losses the output from these plants to the load.

Routine meter testing, checking of relays and protective equipment, system voltage surveys, and routine checking of equipment are carried out in a regular program. Daily reports show system performance setting out distribution of energy and its source at generating plants. Accompanying these is a statement of all unusual conditions, line interruptions, etc.

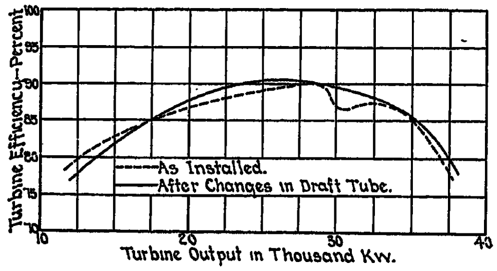

FIG. 2—GRAPH SHOWING INCREASE IN TURBINE EFFICIENCY AFTER CHANGE IN DRAFT TUBE

Solid line shows efficiency after a hydraucone was installed

Reports from individual plants show the details of operations. Steam-plant reports include a heat balance for the day's operation, and hydro plant reports show a record of water used, stored, or passed over the spillway. At the hydro plants records of the operation of the wheels at the gate opening used and the discharge through the spillway gates are employed to check the stream-flow gages. At an earlier period the results from tests of models and the specifications of the manufacturers were used for rating of the wheels. For some time there has been in progress a series of tests which will include one unit of each of the various sizes and manufacture. To date these tests have been of high value.

An example of extreme value is shown in the accompanying graphs in Fig. 2. The broken line shows the characteristics of the hydraulic unit as first installed, and the solid line, the improvement made through a change in the draft tube by installing a hydraucone.

It is often possible to install at the time of testing a pair of piezometers in the penstock and scroll case so arranged that the differential may be determined by the use of a manometer and the values plotted in terms of water flow and thus be available for check runs at any later date.

It is found that a careful audit of stream flow and water use, especially for flows less than the capacity of the plant, is of real value in securing maximum output or maximum time operation at gate openings of high efficiency. This, of course, implies a nice cooperation between plant operators and load dispatchers.

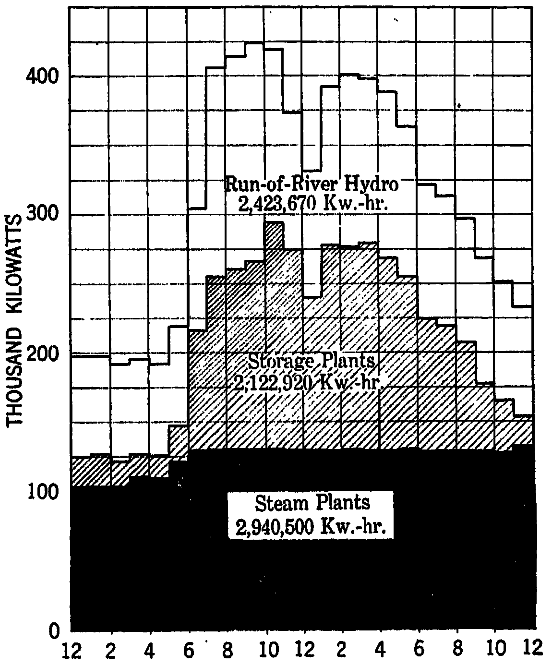

Fig. 3—Load Curve—Typical Day, Normal Dry Month

Load Dispatching

In a system so wide-spread, serving a considerable portion of three states and a part of fourth state which is interconnected, the work of load dispatching becomes extremely important. The load dispatchers must be responsible for coordinating the entire system, not only for daily and weekly runs but they must follow through for an entire year or even a cycle of two or three years on some well conceived program for coordinated use of hydro plants—both those having storage capacity and run-of-river plants—and the various steam plants, each having its own characteristics of economy and protection to a particular load.

In general, the run-of-river hydro plants are operated on the base load whenever the stream flow approaches the capacity of the plant. During the dry weather such plants are operated on a daily or weekly cycle to secure the maximum output in hours of peak load. On the other hand, those hydro plants supplied from storage reservoirs will be operated on a schedule based on stream-flow variations for a year or even more, and effort is being made to have full reservoirs available for the dry season of each year, including a year of low stream flow. This will permit replacing some of the loss of capacity at the run-of-river hydro plants resulting from extremely low stream flow.

The steam generation will vary widely from a minimum during wet weather seasons, when run-of-river plants are carrying full load, to a maximum during periods of lowest stream flow.

Typical plant operation during a wet and a dry day in a year having ordinary seasonal stream flows is shown on Figs. 3 and 4.

Fig. 3 shows conditions in October of 1927 when the storage plants existing at that time were being used for a considerable output to supplement the run-of-river plants at which the stream flows were low during that month. The steam plants operated throughout the twenty-four hours of the day together with run-of-river energy purchased from the government at Muscle Shoals, which plant was available only on a basis of constant output. The other run-of-river power was blocked into the daily peak together with most of the output from the storage plants.

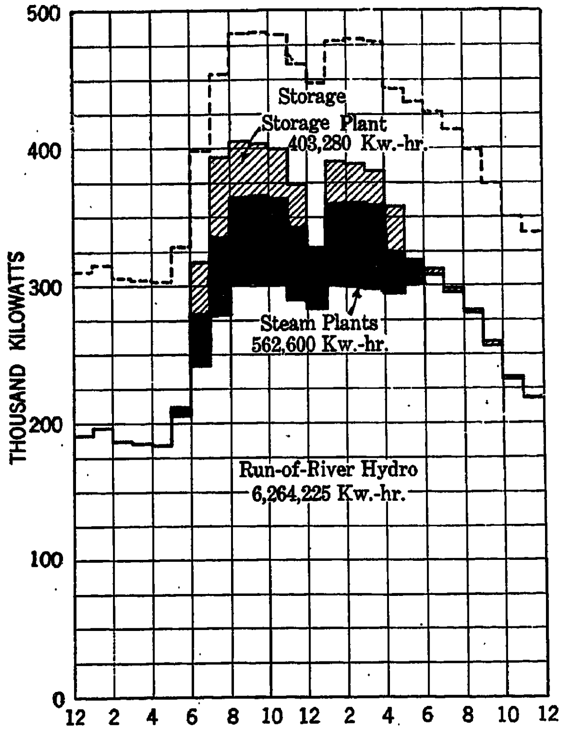

Fig. 4—Load Curve—Typical Day, Normal Wet Month

In a sharp contrast to this, Fig. 4 shows the daily load diagram for March of 1928 under conditions which may be termed normal in wet weather. Storage at this time was being built up, and the most efficient steam plants were being run for a half million kw-hr. daily, as shown, to carry the load with the output from the run-of-river hydro plants and a small output from the storage plants. Stream flow into storage above that used by the plants is plotted above the load curve.

It might be interesting to expand this study into week-end and yearly load diagrams, but the general scheme of operation is set out very nicely by this contrast.

The output from the storage hydro plants of the system in service in 1927, secured by a maximum draw-down, is approximately 230,000,000 kw-hr.

The use of Upper and Lower Tallassee plants, the first finished in June 1928 and the latter to be put into service in 1929, will increase this output through the use of water stored at Martin Dam by approximately 130,000,000 kw-hr. so that the output from stored water in 1930 will have nearly the same ratio to the total load at that time as shown in these load diagrams.

The maximum hourly load carried by the storage plants in 1927 is shown as 165,000 kw. with fairly long-hour use. Capacity available in 1930 will be double this amount with provision in the hydraulic structures for 80,000 kw. additional which may be installed when the proportion of steam generating capacity has greatly increased and the storage plants are pushed higher into the peak. The economy of such added capacity at the hydro plants is based on a cost of construction of about 50 per cent of that for steam units.

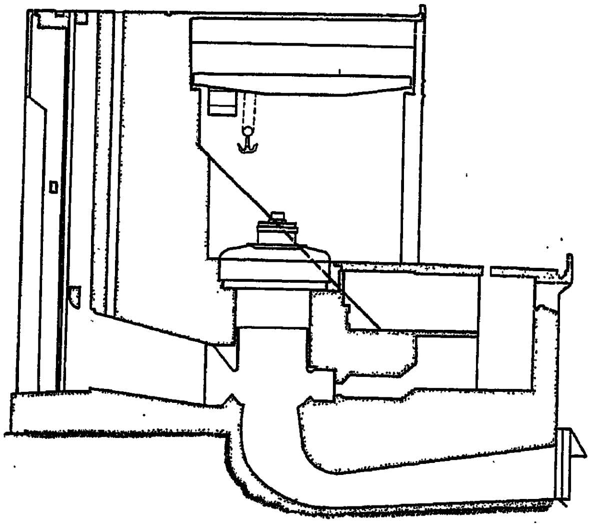

FIG. 5—JORDAN DAM POWER HOUSE
Transverse cross-section through center line of unit

This cost does not include the lines and tie-in facilities and therefore some advantage would be lost if the peak loads to be carried were served over new circuits at a greater distance in the case of hydro units than for steam units. Additional units at existing hydro plants usually call for only an extension of building, a penstock and draft tube, the generating unit itself with the necessary transformer capacity and auxliaries. Additional capacity in steam plants costs the same per kw. as the original plant except (1) for combined use of certain facilities such as real estate, water supply, etc., (2) any saving which can be made by accepting lower efficiency on account of low use factor.

Returning to the subject of load dispatching, it is interesting to note that the schedule for storing and using water at those plants where a considerable stream regulation is possible must take into consideration the cost of steam generation at the various steam plants and an allocation of the load to the lowest cost plants for their maximum use for the required output from fuel, taking reasonable care to avoid a later loss of water from the storage plants. This is, indeed, a most difficult problem and has turned the attention of engineers in the various parts of the country to the study of recurring cycles in weather conditions or stream flow and an attempt at some interpretation which may be used for long time forecast of stream flows. Much of interest along this line has been accomplished, but much more is needed in order to secure anything that may be dependable.

Besides the studies which take up the general economic phases of load distribution between the plants from season to season, there, of course, fall to the lot of the load dispatchers the loading of plants and lines to maintain service under all conditions and to manipulate the use of equipment so as to secure proper voltage conditions through the entire system. To this is added the daily control of streams so as to secure relief from flood conditions and whenever possible obtain full heads at the run of river plants for peak load periods.

SEASONAL MAINTENANCE OF EQUIPMENT

On a system where the only source of supply is from steam plants, there is necessarily provided sufficient capacity so that units may be available in turn as required for inspection. Practically all operating companies make it a practise to inspect the large turbines once every year. On such systems, it sometimes happens that the load demand approaches capacity so closely that the inspection must be made during seasons of low demand, thus making all equipment available for operation during the year's peak.

In contrast with this, it is interesting to note the schedule of inspection and maintenance possible where the plants have a fairly definite seasonal requirement. On this system turbo-generator units at the steam plants are scheduled for inspection during the wet months of the year, which are included in January to June. During this time, besides the regular dismantling and inspection, any pre-scheduled major repairs are also undertaken. Similarly the work on the hydraulic units at the run of river plants is undertaken during the dry months when only a portion of the installed equipment is needed to use the entire stream flow.

REPAIR OF WHEELS BY ELECTRIC WELDING

The largest single item of maintenance of hydraulic units is the welding of wheels to replace metal lost through pitting.

Very rapid pitting of cast iron runners at one of our plants brought about conditions calling for extensive repairs by welding. Cast steel inserts of considerable size were used and the metal of the wheel surrounding these was built up to normal thickness by electric welding.

The results of this work have emphasized to our operators that repairs should not be delayed in the hope that the pitting will cease as a natural course of events. On the other hand, we are convinced that repair by welding should be undertaken just as soon as any considerable area has lost metal to such an extent that a layer of metal placed by electric welding can be used to good advantage.

There has been considerable discussion concerning the use of special metals for surfacing repair sections to reduce the rate of pitting. At this time, the results of the work done for us are not such that we can add anything definite to this item.

Besides such maintenance work, we find it necessary to overhaul completely the moving parts from the servo-motors to and including the wicket gates every twelve to fifteen years. This work includes the replacing of worn liners, bushings, rings, pins, welding up the shafts of wicket gates which may be worn, and, in general, bringing these parts of the machine practically to a new condition.

The schedule for maintenance of equipment at the storage plants may not be forecast as definitely as for the steam plants and run-of-river plants, since a high flow into the pond supplying such a plant may result in the use of these plants on the same schedule as a run-of-river plant at certain periods of the year, and, therefore, the maintenance schedule for these plants is set up only a few weeks in advance. By carrying on maintenance as far as practicable during the season of low generation at the steam plants a further benefit is secured, namely, the reduction in labor turn-over and a more advantageous use of the force of men necessarily continuously employed at the steam plants.

Modern steam-electric units should be available for use 85 per cent of the time. With spare units available to permit inspection and repair, the factor of availability, when required, should approach 100 per cent. By means of scheduling inspection as outlined above, we have obtained a factor of availability, when required, of 99 per cent for three years, and of 99½ per cent for the year 1927.

HYDRAULIC STRUCTURES

Throughout the history of the subsidiary companies of the Southeastern Power & Light Company there has never been any necessity for repairs to hydraulic structures at any of the major plants. The Upper Tallassee Plant, built in the nineties for the Emerson-McMillan Company, was destroyed by a flood in 1920, before being purchased by the Alabama Power Company. This dam was replaced in 1924, using the equipment at the old plant, and since that time has been raised so as to secure a 58-ft. head and a new plant has been built. The erosion of concrete from the spillway sections of any of the dams is thoroughly negligible, and at the oldest plant on the Coosa River, Lock 12, a survey of the river bed immediately below the dam shows excellent conditions.

In the foregoing paragraphs we have touched very briefly upon those features of system extension, operation, and maintenance which seem to us to present points of at least passing interest. A great deal of additional detail is of course at hand, but its presentation is scarcely warranted when so many of the subjects touched upon have been discussed at great length in various articles in the technical and trade press.

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Discussion

ECONOMIES IN CENTRAL POWER SERVICE

(LEE)

SOUTHEASTERN POWER & LIGHT COMPANY'S SYSTEM

(HUTCHINS)

ATLANTA, GA., OCTOBER 29, 1928

W. E. Mitchell: The system that Mr. Lee has built up, in the Duke Power Company, is very nearly ideal. He started out with a hydro system, and fortunately he was able to find load centers interspersed between his logical and economical hydro developments, which made it possible to shift load back and forth, and to get power to the market with the shortest transmission lines. He was working then, for this dollar economy which he has been telling you about. Then, as in other utility companies which have started with hydro developments, he found very soon that the so-called unlimited amounts of water became very much limited as compared to the market, and he was forced to go to some other form of power. With Mr. Lee, as generally in the Southeast, it has been coal. Some in other places will go to oil.

In the Southeastern Power and Light Company when we came to installing these steam plants, we must locate them on ample bodies of cooling water, and of course as close to the load as possible. This didn't happen by chance. It came through thorough study and weighing of load centers, transmission cost, and all other items. We haven't been quite as fortunate in the plant locations as Mr. Lee. A large part of our hydro development in the state of Georgia is up in the northern part, and we had to come 100 miles to get to the main load. In Alabama, it was in the southern part, and we had to carry the power north. But with the growth of those systems, exactly as in the growth of any system, we are finding that now as we build the steam plants we are getting a better distribution of plants with reference to load, which is going to make for more economic use of all our transmission lines.

We are also learning a lesson that Mr. Lee has explained, of the value of the base-load steam plants as plants for filling up the storage reservoirs. Studies very much more thorough have been made in the last few years, of our available water in the effort to get out the last kilowatt-hour. As an example, we started up steam plants in April this year to make certain of having storage reservoirs full on the first of August.

As we learn more about the river flows, as we develop readings over a greater number of years, I believe the time will come when we can forecast still more accurately our available water, and the cycles in which it is likely to come, which will permit of more complete use of it, and that will mean, of course, more economical power development.

In this section of the country which some may think is rather backward, the first real interconnection of a high-voltage type of high capacity was made, between Mr. Lee's system and the system of the Georgia Power Company. One of the next largest interconnections was between the Georgia Power Company and the Alabama Power Company.

We learned years ago the value of coordinated effort and of interlinking the systems of different companies and so have got the benefit of the diversity of these different systems. This, of course, was brought out most clearly in 1925, during the very severe drought when power was shifted from system to system so that actually power generated at Muscle Shoals was available up in North Carolina, some 600 miles away, keeping mills at work that would otherwise have been idle. That is one of the benefits that has come from this closer coordination between the systems. In the individual systems, we go still further. As the systems get larger, we can get more out of each kilowatt capacity that we install. We ought to be able, I believe, to install each kilowatt capacity at a lower dollar cost, and it ought to be a more efficient kilowatt-hour when we get it. I am talking of dollars, not thermal efficiency, because we often lose sight of that. In our business we ought to be interested in the final dollar cost, not thermal efficiency, because that is the thing that it has to be finally measured by. That will tell whether we are going to keep on lowering this cost per kilowatt-hour and developing more capacity per dollar of investment.

W. S. Lee: Mr. Hutchins' descriptions are very interesting. There is a peculiar coincidence, the steam station which is being built by his company and one very similar, being built by my company. The engineering staffs of both companies investigated the matter of type of station about the same time, independently; they came to pretty nearly the same conclusions, so I think I can congratulate him on the type of plant they are building. We are now constructing what we know as the River Bend Steam Station. Two 68,500-kv-a. units at 450-lb. boiler pressure, 725 deg. total temperature, 4-stage bleeding are being installed in this station.

It is interesting to know why both companies decided to use 450-lb. pressure. Preliminary designs and estimates were made by my staff for complete plant at 450-lb., 650 lb., and 1200-lb. pressure. Leaving out the steam generating equipment there was little difference in the total cost of the plant. Steam generating equipment for 450-lb. steam pressure costs approximately 17 per cent of the station. Steam generating equipment for 1200 lb. pressure costs approximately twice as much as for 450-lb. pressure; therefore, the cost of a station equipped with 1200-lb. steam pressure is about 17 per cent over a station equipped with 450 lb.

Out service is for 100 per cent load factor when the plant is operated, and during certain periods of the year there is a total shut-down. This increased cost of installation, with interest and depreciation, brought the cost up so that 1200-lb. pressure was not desirable for our use. Higher steam pressures, no doubt, will be used but they will only be used when the load factor and service can use them at a profit.

The Duke system is not operated normally sectionalized. The system usually works in parallel but in the event of any local disturbance or local storm, the operators immediately sectionalize it to keep disturbances from interfering with other parts of the system.

It is true that as the system gets larger we are forced to use much bigger switches that have a much larger rupturing capacity.

Referring to Mr. Hutchins' discussion of efficiency of water wheels, in our experience we find with a larger system and a great number of units, the operating department often operates more units than are necessary, endeavoring to get advantage of their synchronous effect on the line. During periods of high water there is no loss on this account, but in low water often units operate at a very low point of efficiency. We require the operating department to send record of the load, number of machines, and output to the engineering department promptly. They are computed by the engineering department and returned to the operating department showing the amount of energy loss due to inefficient load on the water wheels. It requires about three days to get these reports back to the operating department. This has resulted in a great saving in the efficiency on all of the stations.

A. T. Hutchins: In connection with Mr. Lee's comments, I might bring out the conditions existing at our hydro plants during periods where the flow of the river is less than the capacity of the plant. Under such conditions, we operate the units in service whenever possible at the gate opening of maximum efficiency. Units required for standby are run as synchronous motors with the wicket gates closed and the governor set to start opening the gates at about one cycle below common frequency. In this way we get very good standby service and avoid operating units at less than their best efficiency, (the point shown either by test or by manufacturers specifications as the best points). Recently, we have done just as Mr. Lee outlined and are auditing the stream flow against the turbine hours at points of maximum efficiency.

We carry this through the entire year and show accumulated losses based upon maximum efficiency secured by operating wheels with the best gate opening. Furthermore we have sufficient storage capacity on the system now so that we can usually operate the steam plants also at maximum efficiency.

I want to bring out one more point. The map (Fig. 1 of the paper) does not show all of the properties of the Southeastern Power & Light Company. The outlying towns served by only one line may require operation of steam units at certain times in order to protect service and this is provided.

J. M. Oliver: I want to ask Mr. Hutchings what his available methods are for testing hydro units.

A. T. Hutchins: I can say that none of us knows what the limits are on conditions at a hydro plant for a fairly accurate test. We raised a question as to whether or not it would be of any use to attempt a test on these units with so small a volume ahead of the wicket gates on the machines. Professor Allen, the originator of the Allen Method, said that he thought it was possible, by putting the first stage of his apparatus right at the penstock gate grooves, to get sufficient volume so that he could get fair accuracy, but many of us questioned it.

Here in Georgia, they are carrying on now some tests of hydro units. Some of the work has produced what seemed to be very consistent results but their accuracy is certainly questionable.

Carrier-Current and Supervisory Control
on Alabama Power Company System

By W. I. WOODCOCK[1]
Non-member

and

E. W. ROBINSON[1]
Non-Member

Synopsis.—The experience of the Alabama Power Company with carrier-current telephony over power lines and supervisory control is outlined in the paper. A sketch is included of the early development of these systems, and this is followed by descriptions of the systems later installed throughout the Company's territory. In an Appendix extracts are given from the general specifications for the equipment employed in the systems.

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EARLY CARRIER-CURRENT AND SUPERVISORY CONTROL DEVELOPMENTS

No article on the subject of carrier-current and supervisory control on the Alabama Power Company's system would be complete without a brief résumé of early developments along these lines prior to the inception of the major program, which may be said to date from about 1925.

Prior to that time, the company had built up a communication system consisting of about 1400 mi. of telephone line, part of which consisted of separate pole lines on the same rights-of-way with the 110-kv. power lines, most of the remainder being carried on the same poles with 44-kv. and 22-kv. lines. These telephone lines connected various generating plants, primary substations, and local offices, and also had connection with many booths along the rights-of-way. They were also used, of course, for the connection of test sets in cases of line patrol.

Due to the long parallels and comparatively small separation, these telephone lines were usually quite noisy, noise levels often being as high as 500 to 600 noise units. These conditions obtained in spite of the application of standard methods employed by the communication companies to eliminate such conditions. To cope with these troubles, considerable experimenting had been done with the use of high-power telephone equipment, such as "Wonderphones," but such equipment only partially overcame the difficulties.

The communication system of the power company was used for load dispatching, commercial service, ordinary operation and maintenance activities, emergency patrols, etc. The company early had realized that its power service could be no better than its communication system. Consequently, as the system grew and traffic increased, the power company had been very much concerned with the possibilities of expanding the communication system to keep pace with the demands upon it. Recourse could not be had to such expedients as phantoming, etc., used by the signal companies, so that it had been necessary to double circuit many lines. This only partially met the requirements, in that the telephone circuits could usually be counted on to go in trouble with the parallel power circuits, so that they were out of commission just when they were needed most. Furthermore, early difficulties were aggravated as the system grew older and depreciated.

The conditions outlined and a survey of the future brought about a very early and intense interest in other means of extending and supplementing the communication system.

The first development that seemed partially to fulfil this requirement was space radio, so that as soon as this reached a reasonable degree of development, the power company was ready to try it, and in 1922 installed Station WSY at Birmingham, with 250 watts capacity. This was employed largely as an advertising proposition, but the real consideration back of it was for use in emergency load dispatching. Consequently, certain of the generating plants, important primary substations, and district offices, were equipped with receiving sets. This station had a very unusual record in the way of long distance transmission, but during the sleet and snow storms of 1922 and 1923, when practically all the communication lines were put out of commission, it was practically worthless for reaching the near-by generating plants, although dispatching orders broadcast at that time were picked up as far away as Central America. Consequently, it was very soon perceived that space radio was not the answer, and Station WSY was discontinued in 1925.

When carrier-current equipment reached a reasonable degree of development, the power company became interested in this, and in 1924 installed two 250-watt single-frequency simplex sets at stations about 60 mi. apart. It was soon found that this equipment was not sufficiently developed, and that the simplex operation was very unsatisfactory. Furthermore, many troubles in operation were encountered, so that these sets were discontinued in 1925.

The experience with the first two sets when they were working properly, however, gave some insight as to the possibilities of satisfactory carrier-current equipment,

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[1] Both of the Alabama Power Company.

Presented at the Regional Meeting of District No. 4, of the A. I. E. E., Atlanta, Ga., Oct. 29-31, 1928.

and the power company therefore participated in a further trial installation in 1925. Two duplex, double-frequency, low-power sets were installed at substations about 65 mi. apart. This installation was extremely successful, although it had its shortcomings and convinced the power company engineers that carrier current was due for very serious consideration in the future expansion of the communication system.

The foregoing review of the communication situation up to 1925 will serve as an introduction for the later discussions of carrier-current equipment on the Alabama Power Company's system; a similar review of supervisory-control developments is in order. Early the power company had realized the need for some form of supervisory control. It was realized that service could be greatly improved and operating expenses reduced if a satisfactory system could be developed. Therefore, some time prior to 1925, experiments were started with a supervisory control system operating over a telephone circuit and employing d-c. impulses as a means of control. It was hoped that such a scheme could be worked out to provide quick sectionalization and location of trouble on long transmission lines; also, that this scheme could be amplified and made use of in dispensing with attendants at various substations by putting them under the control of some central dispatcher.

The first installation to be made was on the Gadsden-Huntsville line, a sending station being installed at the Gadsden Steam Plant to operate a very inaccessible and highly important sectionalizing switch about 50 mi. from Gadsden. This first application was not very successful, due to lack of reliability of the telephone circuit, induction in the telephone circuit from the parallel 110-kv. line, lack of suitable sensitive relays, and, generally, to incomplete development of the idea. Later, the equipment was entirely revamped, and the sending station located at Huntsville, but again the attempt was not very successful. However, just as in the case of the carrier current equipment, this early installation served to visualize the enormously useful possibilities of such a control system.

1925 EXPANSION PROGRAM

Early in 1925 the Power Company was confronted with a very extensive program of expansion, which involved some major items of communication and supervisory control. For the purposes of this paper three of these will be mentioned and discussed at some length. In the first place, in North Alabama there was an acute need for additional communication between Magella substation (Birmingham), Huntsville, Sheffield, and Gorgas Steam Plant. These points were connected by a loop of 110-kv. lines, but only part of this loop had telephone facilities, and these were becoming very inadequate.

In Southwest Alabama two very long lines were projected, radiating from Lock 18 (Jordan Dam). One of these was to extend through Selma, Demopolis, Meridian, and Laurel, to Hattiesburg, with two possible branches beyond that point. The over-all length was to be about 325 mi. A second line, the route of which was not so definitely decided, was to extend from Lock 18 to Flomaton, with branches to Pensacola and Mobile. The total length of this line was to be in excess of 300 mi. These were to be highly reliable, single-circuit, 110-kv. lines, and were to traverse very lean, but potentially good, territory where existing loads were comparatively small and widely separated. Because of the distances involved and necessity for keeping the cost low, it was planned to use carrier current for primary communication, backed up by a secondary system of communication making use of two insulated overhead ground wires which formed a part of the typical construction proposed for these lines. In that these lines had to be highly reliable and provide great continuity of service, it was proposed to install supervisory-controlled, motor-operated, air break switches for sectionalizing at intervals of approximately 15 mi.

The first parts of this program to come up for active consideration were the North Alabama Loop and a portion of the Mississippi line extending from Lock 18 to Demopolis. Appendix A is an extract from the first set of general specifications covering communication and supervisory-control requirements for these and other projects which came up at the same time. Reference to the appendix will give a clear general conception of the typical carrier current and supervisory-control installations contemplated. These same general ideas have been kept in mind in developing carrier current and supervisory control on the Alabama Power Company's system since the first permanent installations. A study of the Alabama Power distribution system, as shown on the map, (Fig. 1), will afford a clear idea of the present extent of carrier-current and supervisory-control installations on the power company's system.

NORTH ALABAMA CARRIER-CURRENT PROJECT

Due to operating requirements, as well as physical location of properties and infrequent necessity of communication between north and south Alabama, north Alabama was considered as a separate project. Four stations were included in original plans and provision was made for installations at two additional locations when traffic demands warranted. The problem of interference had been given consideration and different types of apparatus for different channels appeared to be a solution. However, unforeseen troubles developed, which will be mentioned in detail later.

Stations under consideration were located roughly at the points of a quadrilateral as indicated in Fig. 1 (Index 1). Maximum distances involved were approximately 150 mi. with parallel circuits between all locations. Communication was required from chief dispatching point to all other stations for operation, and in addition, inter-office communication for commercial purposes was essential and necessitated wire line varying in length from 1½ to 4 mi. Carrier equipment was to be coupled to 110-kv. lines, forming a loop, constituted of a single circuit in certain sections and parallel circuits in others, and including a 44-kv. parallel for approximately 65 mi. (Magella to Anniston) on one branch, and approximately 50 mi. (Magella to Jasper) on the other branch of the loop circuit. Both 110-kv. and 44-kv. lines extended beyond the loop circuit into other territory. While all lines were normally tied in parallel, operating procedure demanded frequent changes, and any section of the line might be cut out at any time to meet a specific maintenance or operating problem.

Apparatus decided upon and purchased was of the double-frequency duplex type, having a nominal low power rating of one watt intended for regular operation, and high-power rating of 50 watts for use under abnormal line conditions or severe atmospheric disturbances. Antenna coupling was decided upon due to trouble previously experienced with early types of coupling condensers, and due to cheaper construction possible with antennas without sacrifice of efficiency, (as indicated from test installations). Space available at two locations permitted installation of equipment in substation operating rooms, at one other location construction of a separate carrier current house was necessary, while at the fourth location, a steam plant, equipment was installed on the top floor of the building and necessary control and telephone leads carried to the operating room—a distance of approximately 500 ft. As would be expected, costs of the installations varied widely. However, installed costs per set, exclusive of overhead, averaged $9394.00 per station. This total was split approximately as follows:

Antenna installation—labor and materials....	$1200.00
Carrier-current apparatus..................	5570.00
Miscellaneous material and carrier-current apparatus installation costs...............	2624.00

Operating Results. The first two stations installed were at Magella and Sheffield, approximately 120 mi. apart, and operated satisfactorily on low power from station to station under normal line conditions. High-power range appeared adequate to meet routine switching conditions and operating set-ups. When an intermediate set was installed (Gorgas), trouble began to appear on terminal equipments due to difficulty in making adjustments to accomodate high-energy levels from near-by sets to avoid howling, and yet be sufficiently sensitive to hear distant station. Installation of the fourth set further complicated the operating problem by increasing maximum distance to 155 mi. and requiring more sensitive adjustments on terminal equipments. Received energy levels varied widely with switching on 110-kv. lines, and were so low as to make adjustments of relays extremely difficult over the range of line conditions encountered. It was also found that switching on parallel 44-kv. lines affected received energy levels sufficiently to cause ringing failures. At about this time a short tap line to Wilson Dam was constructed, which constituted a low impedance shunt on the low frequency (70 kilocycles) and necessitated the continuous use of high power for routine operation with approximately the same over-all results as previously obtained on low power. At a later date, a second tap line was constructed to Decatur substation, which effectively shunted the high frequency (104 kilocycles). Since equipment was already being operated on high power, and output could not be increased due to inherent limitations of equipment, trouble was practically overcome by a shift in frequency to 120 kilocycles.

When equipment was first installed, lines normally operated with loop circuit closed. Later it was found necessary to split the circuit at Sheffield. This change produced a marked reduction in received energy between terminal stations and required relay adjustments too close for reliability. It was found impossible to make relay adjustments sufficiently stable to pick up and hold during conversation, and yet release when conversation was finished, under varying line conditions encountered in daily operation. Adjustments could be made for a specific line condition, but any change resulted either in incompleted rings or in relays freezing-in and effectively putting equipment out of commission. The margin between normal space current of receiver tubes and received signal was so small that any relay adjustment sensitive enough to pick up signal was so close that a slight change in battery voltage and resultant change in plate current caused relays to pick up and freeze, thus making the equipment inoperative.

Interference. A few months after equipment on the North Alabama loop had been put into service, more powerful equipment was installed in Southwest Alabama with a set at the chief dispatching point, Magella. Immediately troubles due to interference were encountered. Even though frequency separation of equipments was more than 20 kilocycles, it was found that when one of the more powerful sets was in use all equipment on the North Alabama loop was held inoperative. In commercial equipment, elimination of interference between transmitter and receiver of a carrier-current installation is necessary for acceptable results. This feature on the equipment under consideration was obtained by means of cut-off high- and low-pass filters for separating transmitted and received energy. As a means of eliminating inter-channel interference selection of an operating frequency on interfering equipment between cut-off limits of high- and low-pass filters was considered and tried out. It was found, however, that capacity of filters was not sufficient to block interfering energy and trouble was not materially lessened.

Prior to this time the problems of lack of volume, failures to signal, and howling on office extensions, had been taken up with manufacturers and remedial measures tried as suggested, without much success. Results indicated that equipment did not have enough power to work reliably over distances involved, taking into account the rather complicated network and tap lines. The new problem of interference was brought to the manufacturers' attention and a formal complaint made on performance of equipment. The manufacturer made a complete field study of the problem under normal operating and varying line conditions. Fig. 3 shows curves of received energy under two specific line conditions. In Curve No. 1 parallel circuits were available between stations under test, Curve No. 2 having been taken between the same stations over a single circuit. Minimum energy level for acceptable operation is indicated by dot and dash line. It will be noted that the energy levels were materially less over a single circuit, and that while curves have the same general form, there has been some shift in peaks with the frequency. A direct comparison of quality of talk cannot be made from curves, however, since the two branches of the parallel circuits were of different length and the maximum received energy includes an out-of-phase component, which introduces some distortion. From the signaling point of view alone, received energy is a true index of reliability of ringing and relay adjustment is much simplified with increased energy levels.

The final results of tests conclusively demonstrated that equipment was not suitable to meet operating conditions imposed by length of lines and complicated network, combined with switching met in routine operation. A satisfactory adjustment was made by the manufacturer, and equipment was maintained in service for the time being, on a station to station basis, largely as a standby.

At about the same time, one of the branch circuits was changed over to 154 kv. by means of auto-transformer step-ups effectively open-circuiting the line from a carrier-current standpoint. It has been found possible, however, to use a land line from Magella to Gorgas as a wire line extension, tying into carrier current equipment at the latter location, and carry on a fairly satisfactory conversation between Magella and Sheffield in case of emergency.

Experience with this equipment has shown the necessity of using more power when tying into a complicated power network as compared to commercial practise over straight-away lines. Means must be provided for using as narrow a frequency band as possible, not over 5 to 8 kilocycles maximum, because of necessity of multiple channels, and this band should tune rather sharply to minimize interference.

SOUTHWEST ALABAMA CARRIER-CURRENT PROJECT—(MISSISSIPPI LINE)

After general specifications for the Southwest Alabama project, as covered in detail under Appendix "A," had been worked out, the final set-up was somewhat changed to conform to later developments. The Mississippi line channel, as finally decided upon, contemplated communication over a maximum distance of approximately 325 mi., as indicated in Fig. 1 (Index 2). Installation of ten sets was decided upon, seven of which were required to talk to all other sets of equal capacity, and three were of lower capacity, from which communication was required only to adjacent large sets, a maximum distance of approximately 55 mi.

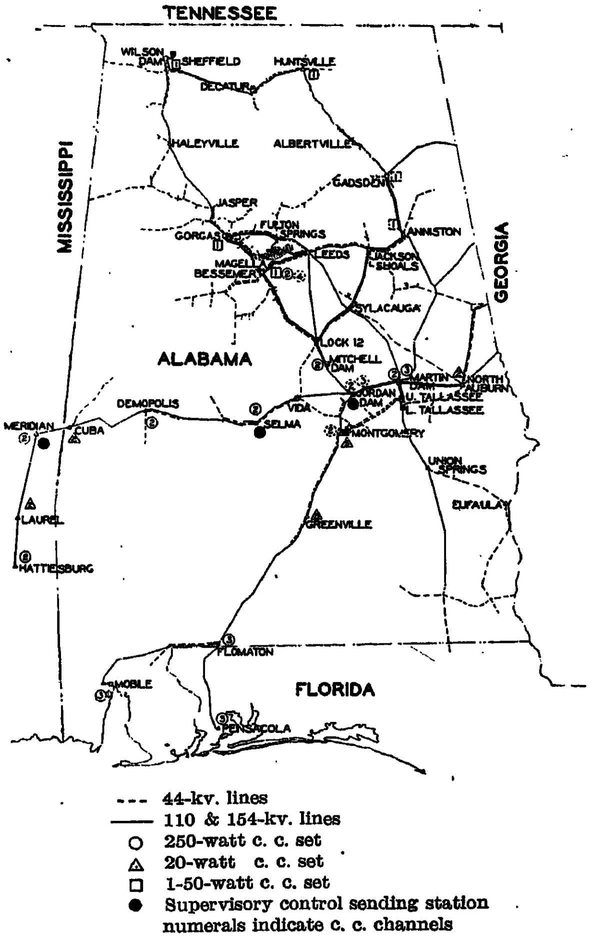

FIG. 1—ELECTRIC DISTRIBUTION LINES IN ALABAMA AND PORTION OF FLORIDA AND MISSISSIPPI

Antenna coupling was decided upon, except for one location (Martin Dam), where physical location of lines and bus structures would have made necessary a double antenna and expensive construction due to an extremely long span over a river. At this location, coupling condensers were installed and connected to substation 110-kv. buses by a remote electrically controlled gang-operated change-over switch. Normally, both station buses are operated in parallel, but the change-over feature of connecting condensers permits either bus to be isolated when necessary for maintenance or repairs without interfering with carrier-current operation. Condenser connections and change-over switching facilities are shown in Fig. 4. Condensers are of the mica dielectric type, and to date have proved entirely satisfactory. Operating results show that there is little, if any, gain in efficiency obtained by using condenser coupling, and final decision on condenser or antenna coupling for any specific installation should be based on economic conditions, rather than on operating efficiency.

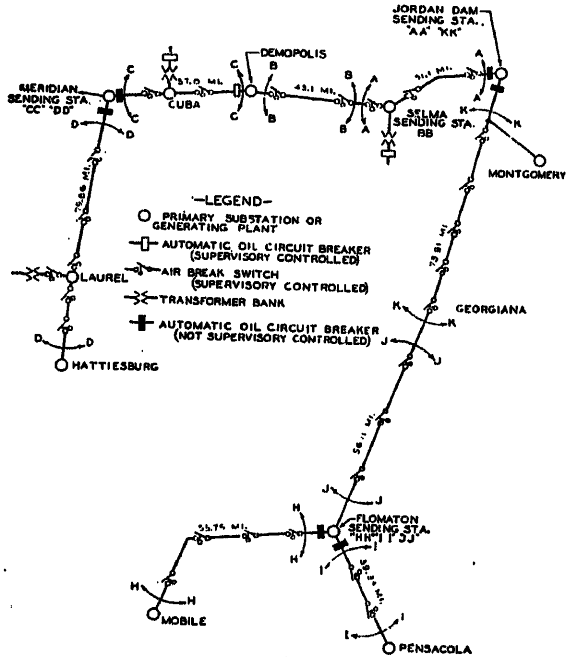
JORDAN DAM SENDING STA. "AA" "KK"
DEMOPOLIS
MERIDIAN SENDING STA. "CC" "DD"
CUBA
37.0 MI.
43.1 MI.
SELMA SENDING STA. BB
MONTGOMERY
75.86 MI.
73.81 MI.
LAUREL
GEORGIANA
HATTIESBURG
56.11 MI.
FLOMATON SENDING STA. "HH" "II" "JJ"
55.74 MI.
MOBILE
PENSACOLA
A
B
C
D
H
I
J
K
—LEGEND—
PRIMARY SUBSTATION OR GENERATING PLANT
AUTOMATIC OIL CIRCUIT BREAKER (SUPERVISORY CONTROLLED)
AIR BREAK SWITCH (SUPERVISORY CONTROLLED)
TRANSFORMER BANK
AUTOMATIC OIL CIRCUIT BREAKER (NOT SUPERVISORY CONTROLLED)

FIG. 2—DIAGRAM OF SUPERVISORY CONTROL ON ALABAMA POWER COMPANY LINES

Apparatus purchased and installed is of the double frequency duplex type, having a 250-watt rating for large sets and a 20-watt rating for intermediate sets from which medium distance communication is desired. Transmitters of 250-watt equipments operate from 110-volt, 60-cycle, a-c. station service supply, and motor-generator sets operating off the station storage batteries provide a-c. supply in case of failure of a-c. station service. As originally installed, transmitter change-over switches were manually operated. Automatic change-over switches for transferring transmitters from a-c. station service to motor-generator sets were later installed to provide for full automatic operation. Twenty-watt sets operate direct from station batteries.

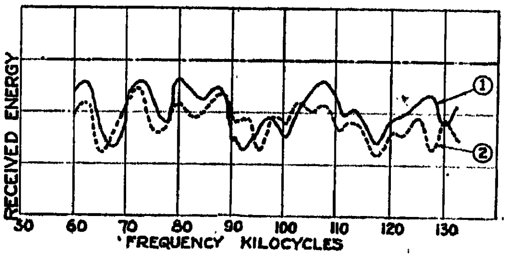

FIG. 3—RECEIVED ENERGY CURVES BETWEEN TWO CARRIER INSTALLATIONS UNDER CHANGED POWER LINE CONDITIONS

Distances between sets average, roughly, 50 mi., and equipment is in all cases installed in substations, several of which are non-attended. Communication demands, as on the North Alabama loop, call for dispatching and commercial service and require wire line extensions at six locations, varying in length from $2\frac{1}{2}$ to 5 miles. Standard telephone spacing is employed on wire line extensions, however, since all line extensions are exposed to interference from power circuits on the same pole lines, special care was exercised to obtain accurate balance and hold noise levels to as low a value as possible.

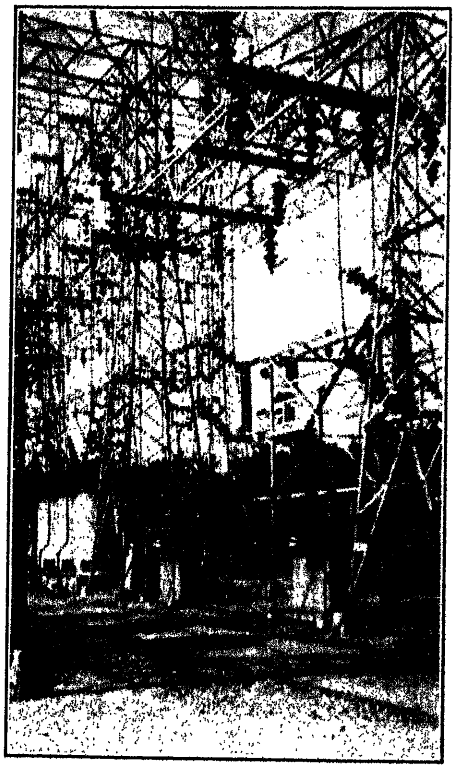

FIG. 4—CARRIER-CURRENT COUPLING CONDENSERS, WITH FUSES AND REMOTE ELECTRICAL CONTROLLED GANG OPERATED CHANGE-OVER SWITCHES AT MARTIN DAM

In all cases, except at Magella, full automatic control is desired from office extensions, and direct signaling is required. At Magella a telephone operator is on duty during office hours and switching to office extensions is done manually. A very special problem with respect to line extensions exists at this location. Four land line trunks connect Magella dispatching station with Birmingham office building, these lines being used for connecting any stations of a private automatic exchange to land lines radiating over the older portions of Alabama Power Company territory within approximately a 100- to 150-mi. radius. It was desired to use any one of these office trunk lines as a carrier current extension for any telephone connected to the private automatic exchange in the Birmingham office building. Since two-wire extensions are used at other installations, a very accurate hybrid coil balance is necessary to prevent feed-backs and howling. This problem of balance was satisfactorily solved by manufacturer's engineers and any private automatic exchange telephone in the Birmingham office building can be connected to carrier current equipment. Outgoing calls are placed with Magella operator in the same manner as a long distance call is given to a private branch exchange operator. Incoming calls are answered by the Magella operator, who, in turn, dials office telephone desired, using any idle trunk line.

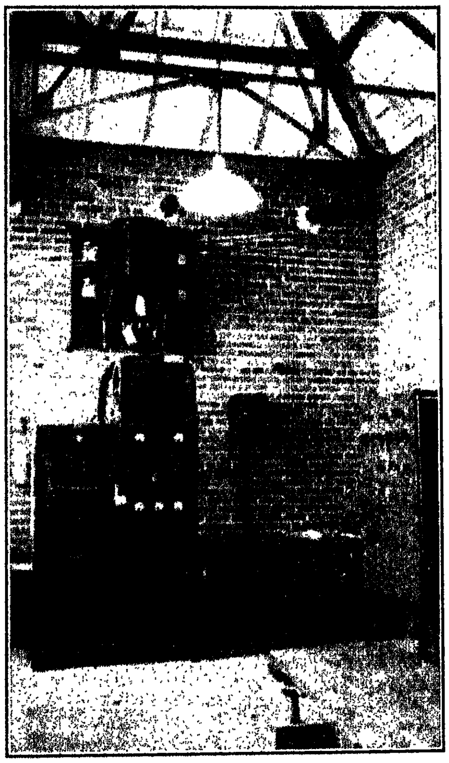

FIG. 5—250-WATT CARRIER-CURRENT TRANSMITTER AND RECEIVER WITH TWO-WIRE TUNING UNIT AT MARTIN DAM

Carrier-Current Installations. A typical carrier-current installation on the Mississippi line using antenna coupling, is shown in Fig. 5. A separate room is provided for carrier current equipment, which is also used for supervisory control sending equipment at several locations. Antenna drainage and protective equipment is mounted on a special structure. The same protective equipment is used at the condenser-coupled installation, mounting details of which are shown in Fig. 4.

Interphase coupling is used at all locations for transmitter, while at some locations the receiver is coupled phase-to-ground, using a third wire for receiving antenna. At other locations, phase-to-phase coupling is used to obtain combined transmission and reception on a phase-to-phase basis, using a special tuning unit as shown above transmitted in Fig. 5. Selection of receiving method was made in all cases by trial to obtain best results or to overcome some special problem.

During installation a number of unusual problems was encountered, a detailed discussion of which is beyond the scope of this paper. Among these may be mentioned balance of exposed wire line extensions, provision of a system busy and lockout signal except at dispatching points, adjustments to provide for transmission from end to end of system and at the same time communicate with adjacent sections. The solutions of these problems were worked out as the problems presented themselves, and operating equipment was turned over by the manufacturer's engineers in a working condition and taking care of all special requirements.

Approximate average installed cost of a 250-watt set was $10,500.00, exclusive of general overhead and wire line extensions; of a 20-watt set, $6,050.00. Per mile costs are apt to be misleading and no definite figure can be given that will apply to other than a specific location. The same is true of cost comparisons between land line and carrier-current installations. On the specific line under consideration, carrier-current installations are separated approximately 50 mi., and size and importance of intermediate towns is such that necessity for future installation of additional sets appears remote. Under conditions such as outlined, a carrier-current installation meets all requirements except for emergency patrols, and shows a marked saving over a land line. Complete operation and maintenance costs are not available, but incomplete figures indicate that the average cost will not exceed $500.00 per station per year, and probably will be materially less.

Operating Experience. Operating experience has shown the necessity of routine inspection and maintenance by a trained personnel at regular intervals. A special daily operating report form has been adopted which gives a record of performance and indicates units such as tubes or batteries that are nearing the end of their useful life. These report forms are forwarded to carrier-current maintenance men, and failing units are checked and replaced, if necessary, on the next regular routine inspection. Field forces keep the batteries filled, replace burned out tubes, and keep the equipment clean, but have definite instructions not to change any adjustments or make any modifications or additions either to carrier-current equipment or line extensions. Operating results have, in general, been quite satisfactory, and an over-all efficiency of 93.7 per cent has been obtained on 250-watt sets. Complete records are not available on intermediate 20-watt sets, but operating results have not been as good, probably due in large measure to a less completely worked out design.

Equipment, with exception of line extensions, has been free from trouble due to lightning or surges. Line extension troubles due to above causes have been confined in all cases to circuits external to carrier-current equipment, and have consisted of blown fuses and destroyed vacuum bulb arresters. In several instances of direct contact between line extensions and power conductors (11-kv.), line protective equipment successfully cleared the trouble without damage to carrier current sets or extension telephones. However, line surges and lightning frequently cause incorrect or incomplete rings. During lightning storms, it is frequently necessary to dial a given station several times before a correct ring is obtained.

When the equipment was first put into service, considerable trouble was experienced due to burn-outs of 50-watt tubes used in speech amplifier and master oscillator circuits. These tubes were replaced by manufacturer with a later design that has given excellent results. To date, not a single tube has failed in over nine months' service. Life of all other tubes, with the exception of rectifier tubes on battery charging equipment, has been satisfactory. Rectifier tubes of the vacuum bulb type used for floating control (18-volt) and receiver filament (6-volt) batteries, have given life comparable to this type of equipment in continuous service, but not up to standard of life obtained from vacuum tubes in carrier-current equipment proper. Receiver plate supply is obtained from a rectifier across which is floated a dry type "B" battery to provide for continuous operation in case station service a-c. supply is interrupted. It was found that the regulation of the rectifier was such that voltage did not remain constant, but built up to approximately 50 per cent above the nominal "B" battery rating before a stable condition obtained. The consequent change in plate current caused failures in relay operation until it was found that this abnormal voltage was not a transient condition, but maintained for hours after a-c. supply was interrupted. Relay and bias battery adjustments were changed to conform to maximum stable plate supply voltage, and troubles from this source were eliminated. Considerable trouble was experienced on wire line extensions, due to inductive pick-up. Noise was not only transmitted, but destroyed the quality of outgoing talk. It was found necessary to re-transpose several line extensions, and in all cases keep lines absolutely clear from grounds to obtain satisfactory results. Other equipment troubles have been of a rather minor nature, such as sticking relays, blown fuses, loose connections, and failures of specific units, such as condensers and transformers.

Open Switches. Any change in a power system set-up is reflected in energy levels received at carrier current equipments and affects communication to some degree. It has been found that communication is possible in practically all cases, as long as there is a complete metallic circuit between sending and receiving stations, provided adjustments in equipment have been made to accommodate the worst, rather than normal, operating conditions. Communication across open switches on single circuit power lines cannot be made dependable without auxiliary by-pass equipment and a reduction in over-all efficiency. On several occasions, successful communication across an open breaker was obtained by retuning carrier current equipment. This, however, necessitated rather critical adjustments by a trained personnel, a condition that could not be obtained in normal operating procedure. Results obtained, therefore, cannot be considered commercial.

On a specific section of single circuit line (Meridian-Hattiesburg) on H-frame structures and having insulated overhead ground wires, (see Fig. 6, for construction), it has been found possible to signal and talk with a fair degree of reliability, without retuning, across as many as four open switches. Power conductors are 397,000-cir. mil aluminum. Insulated overhead ground wires in this section of line are composite steel-aluminum cables, having three strands of aluminum and four of steel (with a d-c. resistance of 3.4 ohms per mile), and are transposed at approximately 4-mi. intervals. These results are apparently due to direct coupling, rather than to distributed capacity between power conductors and insulated overhead wires acting as a by-pass condenser, since in all cases overhead wires are transposed at open switches referred to and at three intermediate points. From a carrier current standpoint, this is essentially a double circuit line, and results obtained do not modify preceding statement relative to communication across open switches on single circuit lines.

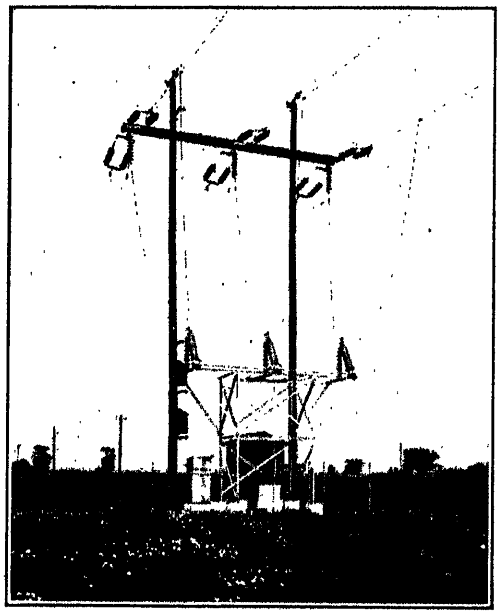

FIG. 6—SUPERVISORY CONTROLLED 110-KV. SECTIONALIZING SWITCH BETWEEN SELMA AND DEMOPOLIS

Prior to the use of carrier current over power conductors, communication facilities of power companies were entirely separate and additions to or modifications of power lines were made without affecting the communication system. Installations of carrier-current equipment have entirely changed this condition, and complete information on changes in operating procedure, as well as line modifications or additions, must be transmitted to the communication engineers if maximum results are to be obtained. A short tap line may constitute a low impedance shunt, or a transformer bank installation may effectively open circuit a line, at carrier-current operating frequencies, and remedial measures must be taken if carrier current equipment is to remain operative. As a typical example, it is proposed to operate the Alabama Power system in the near future, split at Jordan Dam. This proposed operating change will necessitate a carrier current by-pass at Jordan Dam to tie the Mississippi channel through. Necessary materials are on order, so that when this change becomes effective communication will not be interrupted.

SOUTHWEST ALABAMA CARRIER-CURRENT PROJECT—(MOBILE LINE)

Stations on the Mobile channel, as indicated in Fig. 1 (index 3) are, with one exception, fed by a single circuit 110-kv. line. Typical construction of this 110-kv. circuit is the same as used on the Mississippi line, except that insulated overhead wires on the entire line are composite steel-aluminum cables. This insulated overhead ground wire circuit is continuous, and the desirability of using it as a carrier current channel to avoid interruptions to communication from open sectionalizing switches, is readily evident. To determine the feasibility of using this circuit, a 60-mi. section of line was isolated and measurements of attenuation and line characteristics made. Results obtained[2] show this circuit to be commercially practicable, and decision was made to couple carrier current equipment direct to insulated overhead ground wires. Communication requirements are the same as on the North Alabama loop and Mississippi line channels, and include office line extensions at two locations, approximately 4½ and 12 mi. long respectively. Coupling is direct to the insulated overhead wires by means of 0.001 microfarad condensers having a 15,000-volt rating, and protective equipment is essentially the same as that used on the supervisory control system at receiving stations. All installations are now complete, but equipment has not yet been put into service. A typical installation of transmitter and receiver is shown in Fig. 5. Costs are not yet available, but it is believed that costs will be somewhat less than on the Mississippi line, since antenna construction was not necessary.

SOUTHWEST ALABAMA SUPERVISORY CONTROL PROJECT

The supervisory control installation as finally worked out for the Jordan Dam-Hattiesburg line was somewhat different from that outlined in specifications of Appendix A. In the first place, Jordan Dam was developed sooner than expected, so that the first control station was located there instead of at Mitchell Dam. Secondly, the line was terminated at Hattiesburg, instead of extending beyond that point. Otherwise, however, the final installation followed quite closely the original specifications. In discussing supervisory control on the Alabama Power system, this line was taken as the best example, since it is typical, and is the oldest and most complete of the supervisory control installations.

The Mississippi line is a 110-kv., single-circuit line. The supporting structures are creosoted pine H-frames, carrying, for the most part, 397,500 cir. mil steel reinforced, aluminum conductors, suspended by 8 unit suspension insulators. The power conductors are spaced 14 feet apart horizontally, and, about 9 feet above and between them, there are two ½-in. Siemans-Martin steel ground wires, carried on the projecting tops of the poles. These are insulated by 20-kv. pin type insulators or suitable strain insulators. The insulated overhead ground wires are transposed at intervals of approximately 4 mi. At the various substations they are carried in to the supervisory control and emergency telephone equipment through appropriate protective devices. At 2-mi. intervals drops extend down the poles, on 20-kv. insulators, from the insulated overhead ground wires and are terminated at suitable protective equipment so that patrolmen may use the insulated overhead ground wires as a communication circuit in emergencies. At approximately 15-mi. intervals, and at the substations, there are motor operated, supervisory controlled, air break sectionalizing switches. Also, at some of the substations,—Selma, Demopolis, and Cuba,—there are certain supervisory controlled oil circuit breakers.

Fig. 2 shows the various supervised switches on the Mississippi line. A short discussion will demonstrate the typical functions of these switches. Assume a case of line trouble just north of Laurel. The oil circuit breaker in the Laurel line at Meridian opens automatically, all others remaining closed as they are controlled by properly coordinated relay installations. This breaker would reclose twice automatically, and then lock out. The Meridian operator would then open the first sectionalizing switch south of Meridian by supervisory control, and test the line that far. Obviously, it would test good. He would then close the first switch and open the second switch by supervisory control, and get a second good test. However, when he closed the second switch and opened the third, (at Laurel), and tested, the test would be bad, and he would know the trouble was in the first 15 mi.

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[2] Telephone Communication over Power Lines by High-Frequency Currents, by C. A. Boddie.

north of Laurel. All this would be done in a few minutes, and the maintenance crews would be promptly on their way to the trouble, with only 15 mi. of line to patrol instead of about 50 mi., as would be true without the supervisory controlled sectionalizing switches. Similar analyses will demonstrate the purposes of the other supervised and non-supervised switches and oil circuit breakers.

Supervisory control is usually considered to be extra remote electrical control, generally employing the ordinary dial and selector mechanisms of the automatic telephone, with some sort of electrical control circuit connecting the sending (dial) and receiving (selector) stations. There is also usually some form of answer-back signal to indicate the functioning of the controlled equipment. The control circuit may be a simple two-wire telephone circuit employing a-c. impulses; it may be a power circuit carrying superimposed carrier impulses; it may be space radio; or it may be some other form of circuit carrying some form of impulses.

The Alabama Power Company's specifications, Appendix A, brought forth two general proposals. The first was to use the power conductors to transmit carrier-current impulses to operate the supervisory equipment. This involved the use of carrier-current sets and antennas separate from those provided for communication. The second proposed the use of the insulated overhead ground wires to carry alternating-current impulses of medium frequency (450 to 600 cycles) which were to operate the supervisory controlled equipment and were to be obtained from small motor-generator sets operated by the station control batteries. These impulses were to be put on and taken off the insulated overhead ground wires at substations and sectionalizing switches by means of special insulating and drainage transformers. The middle points of the high-tension windings were to be grounded, thus providing ground connections for the insulated overhead ground wires. These transformers were to be so designed and protected as to provide low impedance paths to ground for high-frequencies from either ground wire, to insert comparatively high impedance between ground wires for frequencies of 600 cycles and less; they were to provide ample insulation between the ground wires and the supervisory control and emergency telephone equipment, and, finally, they were not to interfere with the use of the insulated overhead ground wires for audio communication. As to functioning, it was proposed that the operator at any control station might ascertain the position of any supervised switch or breaker in his control section. If open, he might close it, and if closed, he might open it. In the two latter cases he was to get an indication of correct and complete operation. Various safeguards were provided, the most interesting being the use of 450 cycles to set up the relays ready for operation, and 600 cycles actually to perform any operation. Actual operation of the switches as outlined in Appendix A was to be by means of motor mechanisms driven by the local 12-volt or 110-volt storage batteries.

The second proposal was adopted as being the most feasible, least expensive, least complicated, most reliable, and as involving the fewest untried items of equipment. Although many difficulties were encountered in designing, installing, and putting into operation this equipment, this choice was later proved to be amply justified.

A more complete description cannot be attempted within the scope of this paper. Some data follow which will be of interest and value in forming an opinion of this type of supervisory control equipment; and in passing, it might be said that every objective set forth in the original specifications had been attained,—even to the charging of the 12-volt control batteries by means of drainage from the insulated overhead ground wires.

The cost of the entire installation on the Mississippi line, exclusive of general overhead, and not including insulation of the overhead ground wires, amounted to about $38,000. The cost of the original supervisory equipment installed for a typical sectionalizing switch was $2100, and for a typical single line control station $2225. Equipment costs have since increased, and present figures would approximate $2700 and $3000 respectively.

All equipment is inspected and tested on a monthly schedule, and so far the operation and maintenance cost have been comparatively low, being practically confined to the time and expenses of the inspector.

The insulation of the overhead ground wires added about $50 per mile to the cost of the power line, exclusive of general overhead, but all of this is not chargeable to supervisory control, as it is also essential to the emergency communication system.

For the period from July 1927 to July 1928, all supervised equipment in the 90-mi. section from Hattiesburg to Meridian was given a monthly operating test with the power line energized, up to and including the motor mechanisms. In this period there was only one failure to function properly, and this was due to improper adjustments at one sectionalizing switch following installation of a new type insulating and drainage transformer which was being tried.

The Alabama section was not in full operation until 1928, but every part of it is now functioning and has been successfully operated on test.

The inspection and testing of all carrier current and supervisory control equipment for the Jordan Dam-Hattiesburg line takes less than half the time of two men.

Insulation of the overhead ground wires and their use for supervisory control and communication does not appear to have materially lessened their protective value, as line troubles have been very few and not of such nature as to be attributable to decreased protective value of the overhead ground wires. Momentary interruptions, in spite of very bad lightning conditions, have been comparatively few, varying from a minimum of 0 to a maximum of 6 per month for the entire line.

The operation and maintenance of the supervisory control equipment is not extremely difficult, nor beyond the capacity of a first-class operator or maintenance man.

CONCLUSIONS

In view of experience on the Alabama Power Company system, the following conclusions as to carrier current communication may be drawn:

It is thoroughly practicable for power lines, but operates better on radial lines than networks. Short taps on lines used as carrier-current channels must be avoided or isolated.

For long distance, it is more reliable and economical than telephone lines.

It has not been satisfactorily developed to take care of patrol work, nor are the intermediate capacity sets thoroughly satisfactory, but this end seems probable of attainment.

Careful study of power circuit characteristics prior to installation of carrier current is essential.

It cannot be expected to operate consistently through transformers or open switches.

Antenna and condenser coupling are equally satisfactory, the choice depending on cost and physical conditions.

Careful, frequent, and competent inspection and reporting are essential to satisfactory operation.

Before embarking on a carrier current program, very careful consideration must be given to frequencies, etc., to provide for a sufficient number of carrier current channels.

There are certain improvements and modifications in equipment that should be made, notably—redesign for cheaper and easier installation; greater accessibility for inspections and repairs; greater factors of safety and wider operating margins; improved battery charging equipment and elimination of "B" and bias batteries if possible.

As to supervisory control on the Alabama Power Company's system, the following conclusions may be drawn:

It is of considerable value in decreasing operating costs and improving service by reducing length of interruptions.

Medium frequency a-c. impulses transmitted over insulated overhead ground wires have been proved entirely practical as a control medium.

Regular, frequent, and competent inspection and reporting are essential to satisfactory operation.

Except for simple forms of supervisory control over ordinary pilot circuits, there is still a great deal of room for development and improvement.

Appendix A—Extract from Specifications—Communication and Control—Alabama Power Company System

PART I—NORTH ALABAMA PROJECT

General. This project contemplates provision for through communication facilities between Magella, Gorgas, Sheffield, and Huntsville. Carrier-current sets called for in these specifications will operate interphase over power conductors, using antenna coupling.

Circuits to be utilized in the above consist in general of H-frame structures, carrying three 110-kv. conductors, in a horizontal plane, these conductors being 250,000 cir. mils or 300,000-cir. mils copper, and spaced 14 ft. center to center. Between conductors and approximately 9 ft. above them, are uninsulated ½-in. galvanized steel ground wires. Antennas will be supported above or between conductors, and not over 10 ft. from same. Antennas will be 1500 to 2000 ft. in length.

No communication facilities are contemplated at present except for the main sets specified below, no provision being made for portable set communication. Operation through open disconnecting switches is not contemplated.

Gorgas Steam Plant. Equipment to be installed at this point will consist of one duplex, single or double frequency, selective ringing, carrier current set. This equipment will operate from station 110-volt a-c. service or in an emergency from a 125-volt station storage battery of ample capacity. Equipment will be installed adjacent to operator, and there will be no long connection between operator's phone and set. Equipment is to be complete with sending and receiving apparatus, operator's phone, ringing equipment, any recommended protective devices, motor-generator sets, and any other necessary accessories. No batteries or cable will be included.

Sheffield. Equipment to be installed at this point will, in general, be the same as that specified for Gorgas Steam Plant, except that set will be installed at a distance of approximately 500 ft. from the operator, and phone at set should be included.

Huntsville. Equipment to be installed at this point will be the same as that specified for Gorgas Steam Plant.

Magella. Equipment to be installed at this point will be the same as that specified for Gorgas Steam Plant.

Operation is not contemplated through open disconnecting switches, but equipment shall be satisfactory for emergency operation with at least one conductor grounded.

PART 2—MONTGOMERY-GREENVILLE PROJECT

General. These specifications are intended to cover all communication equipment necessary for satisfactory operation of the Montgomery-Greenville 44-kv. line.

All equipment will be antenna coupled to the 44-kv. conductors. Intermediate capacity sets will be installed at Montgomery and Greenville, which must be satisfactory for through communication between these points. Portable sets will be used at other locations on the line, which must be suitable for communication with the nearest intermediate set. This line consists of single wood pole structures, carrying three No. 2 copper conductors, two of these being in the same horizontal plane, approximately 5 ft. apart, and the third one being between and approximately 4 ft. above them. Antennas will be of $\frac{3}{8}$-in. galvanized steel, spaced below and outside the two lower conductors, and approximately 3 ft. from them. These antennas will be approximately 1500 feet long.

Montgomery. Equipment to be installed at Montgomery Gas Plant Substation will consist of one intermediate capacity duplex, single or double frequency, selective ringing, carrier-current set, capable of communication with Greenville under all conditions. Operation past open disconnects is not contemplated, but set shall be capable of satisfactory operation in emergency with one conductor grounded. This set will be installed approximately 4000 ft. from the operator, and control will be effected over a 4-conductor line consisting of two No. 14 twisted pairs (or 2-conductor, at option of manufacturer). Set will operate from a 24-volt storage battery of ample capacity, which is already installed. Coupling to 44-kv. lines at this point will be by means of condensers already provided by the Power Company. Proposal must include sending and receiving equipment, suitable for reception of code calls from Greenville, or vocal or code calls from portable sets. Proposal must also include ringing and telephone equipment for installation at the remote operator's station, and telephone equipment for installation adjacent to the set. There must also be included all motor-generator sets, protective equipment, and other accessories which may be deemed necessary. This set shall be suitable for manual connection at the operator's station to the existing 2-wire company telephone circuit extending to our Montgomery office.

Greenville. Equipment for this location shall be the same as that described for Montgomery, except that extension to Greenville office, from which point the set will be controlled, will be only 3000 ft. long. This set will be coupled to the line by means of a 3000-ft. antenna extending 1500 ft. on each side of the line disconnecting switch installed at Greenville.

Line Equipment. In addition to the foregoing locations, there will be 12 points along the line where antennas will be installed for use of portable sets. For these locations, there will be provided 7 portable carrier-current sets, capable of communication between portables for limited ranges, or between portables and the nearest intermediate set from any location on the line. Portable sets shall include transmitting and receiving equipment, and shall be simplex, single- or double-frequency, audible (or selective code) calling equipment. These sets must not exceed 15 lb. in weight, and dimensions shall be restricted as much as possible. Sets and cases shall be substantially constructed, must be weatherproof, and must be provided with straps for carrying in the hand or suspended over the shoulder. There shall also be provided suitable drainage and protective equipment for 13 locations, including the 12 antennas for portable sets and the Greenville antenna. This equipment must be compact, as simple as possible, weatherproof, and suitable for mounting on line structures out of doors. It should be noted that 44-kv. insulated platforms will be provided for the use of operators of the portable sets and that drops will be provided extending within 10 feet of the ground from the antenna conductors.

PART 3—SOUTHWEST ALABAMA PROJECT

General. These specifications are intended to cover control and communication for two main circuits radiating from Lock 18, one of which will ultimately extend 305 mi. to Slidell, and the other 309 mi. to Moss Point. These circuits will be supplied from Mitchell Dam, so that the length from the source of supply will be approximately 325 mi. Magella, Mitchell Dam, Meridian, Hattiesburg, Andalusia, Mobile, Pensacola, and Moss Point will be important control centers, and ultimately communication will be necessary between Mitchell Dam and Magella, and Mitchell Dam and any point on either of the two circuits described, this to be accomplished by through communication or by the use of repeaters in the two lines.

In each of the circuits described, it is contemplated that sectionalizing switches under control of central control points will be installed approximately every 15 mi., and it will be necessary to provide control for these sectionalizing switches, and also control for certain oil circuit breakers.

For communication, it is proposed to provide interphase carrier current sets as detailed later, which will be antenna coupled to power conductors. The power lines will consist of wooden H-frame structures, on which the 110-kv. power conductors will be supported in a horizontal plane approximately 14 ft. apart. Between, and approximately 9 ft. above these, there will be two $\frac{1}{2}$-in. galvanized steel ground wires, insulated for 25 kv. These ground wires will be sectionalized and used for control, as hereinafter described. Coupling antennas will be 1500 to 2000 ft. long, and will be supported above and between conductors, the distances from conductors not exceeding 10 ft. in any case. It should be noted that the ground wires on the line between Lock 18 and Mitchell Dam, and between Lock 18 and Union Springs, are not insulated as described above, but are both solidly grounded. On the newer sections of the line, where the ground wires are insulated, they will be transposed at each sectionalizing point, and at three locations between adjacent sectionalizing points, so that transpositions will be provided at approximately 4 mi. intervals. Drainage equipment will be provided for these ground wires at sectionalizing points, or, in other words, at 15-mi. intervals. These ground wires will be used for emergency communication as described later, and for this purpose, drops for the use of patrolmen will be provided at sectionalizing points and at two mile intervals between sectionalizing points, these drops to be provided with suitable switching and protective facilities.

As previously stated, ordinary communication will be by means of antenna coupled carrier current sets, but it is not contemplated that these facilities will operate through open sectionalizing switches. When a section of line goes in trouble, the sectionalizing switches at control points at each end will be opened, and for the section in trouble communication will be established by means of ordinary telephone equipment over the insulated ground wires. Under these conditions, patrolmen engaged in locating or repairing trouble will communicate with the control stations at either end by means of the drops from the ground wires previously mentioned, and use of ordinary portable telephone sets. Under these conditions, through communication will be relayed vocally at each end of the section in trouble.

Control of sectionalizing and oil switches will be effected over the insulated ground wires previously mentioned, using carrier current or some recommended alternative scheme. The only exception is for the section between Lock 18 and Mitchell Dam, where a standard telephone circuit on separate poles will be provided, this to consist of No. 4 A. C. S. R. This circuit will take the place of the insulated ground wires on the newer sections of line for both emergency communication and control. It is possible that on the Moss Point circuit, recourse will be had to a No. 8 copper clad telephone circuit for similar purposes between Lock 18 and Union Springs, this circuit being in place already.

It should be noted that present facilities at Mitchell Dam and Magella include 7½- 50 watt, duplex, single frequency, selective ringing, General Electric carrier-current sets, operating interphase, which it is proposed to use, if possible, in the ultimate set-up.

Mitchell Dam. At this point it is proposed to use the present carrier current set with or without adaptations, as may be necessary, or if it is not economical to coordinate new equipment with present set, to replace the present set with one of sufficient capacity and suitable characteristics to communicate with Meridian, Andalusia, and Magella without repeaters, or with Slidell and Moss Point by the use of intermediate repeater sets. This set, or any new set which may be necessary, will operate from the 125-volt station storage battery, and will be located approximately 1000 ft. from the operator, the intervening connection being made by means of a multi-conductor lead covered cable. In case it is proposed to install a new set at this point, it must be duplex, single- or double-frequency, selective ringing, and suitable for interphase communication under conditions of operation and installation as set forth above, and must be complete with transmitting and receiving equipment, ringing equipment, telephone and ringing equipment for the operator's station, motor-generator sets, protective equipment, and all other necessary accessories.

The control equipment for Mitchell Dam will operate from the 125-volt station storage battery, and will be installed approximately 1000 ft. from the operator, and adjacent to the carrier current set previously mentioned. This equipment will be under control of the operator, the same as the carrier current set. Equipment shall include transmitting apparatus for control of two oil circuit breakers at Lock 18, one oil circuit breaker at Selma, and five sectionalizing switches. There shall also be included supervisory equipment for giving a visual (or satisfactory audible) return indication of the operation of the two oil circuit breakers at Lock 18, whether under control or automatic, and further, equipment shall be provided for checking the position of these breakers. The indicating equipment will be installed at the operator's station previously referred to. In addition to the transmitting and indicating equipment, proposal shall include all motor-generator sets, selector equipment, protective equipment, and other accessories necessary for the complete and satisfactory functioning of this system of control.

Lock 18. Control equipment to be supplied for this location will include supervisory control receiving and return signal equipment for two oil circuit breakers as previously described, and receiving equipment for one sectionalizing switch. This control will work in parallel with hand control provided at this station. Power supply for this equipment will be from a 24-volt, 120-ampere hour station storage battery, the voltage of which may vary between 18 and 30 volts. Proposal should include receiving and return signal equipment as described, also any protective equipment recommended and any motor-generator sets or other accessories necessary for the complete and satisfactory operation of this equipment, as outlined. The Power Company will furnish necessary storage batteries.

Selma. Carrier-current equipment for this location will consist of one duplex, single- or double-frequency, selective ringing, carrier-current set suitable for interphase operation with antenna coupling, and with sufficient capacity to insure satisfactory and reliable communication with Meridian and Magella. It should be noted, however, that operation through open disconnecting switches is not contemplated, but set should be capable of satisfactory communication, even with one conductor grounded. Power supply for this set will be from a 110-kv., 120-ampere hour station storage battery, voltage of which may fluctuate between 90 and 130 volts. This set will be installed approximately 3½ mi. from the operator, and the intervening connection will be made by means of a 4-conductor, No. 14 twisted pair circuit (or 2-conductor at option of manufacturer). Proposal must include transmitting and receiving equipment, ringing equipment for the set and for the operator's station, telephone equipment at the set and at the operator's station, protective equipment, motor-generator sets, and any other accessories necessary to complete and satisfactory operation. The Power Company will furnish necessary storage batteries.

Control equipment will be provided at Selma for operation of the sectionalizing switches between Selma and Demopolis. This will include transmitting equipment for two sectionalizing switches as indicated on attached drawings. No provision will be made for checking position of these switches. Proposals shall include transmitting equipment, protective equipment, and any motor-generator sets, selector devices, or other accessories necessary to complete and satisfactory operation. Power supply will be from 110-volt, 120-ampere hour station storage battery, and operator will be located at the control set when it is necessary for same to be operated. Control equipment for this location will also include receiving equipment for operation of one oil circuit breaker and one sectionalizing switch from Mitchell Dam, but no provision shall be made for checking their position. This equipment will operate in parallel with the hand control provided at this station, and shall include all accessories necessary to complete and satisfactory operation.

Demopolis. A duplex, selective ringing, single or double frequency carrier current set for interphase operation, with antenna coupling, shall be provided for this location. This set will operate off of the 24-volt, 120-ampere hour station storage battery. The operator will be located approximately 3½ mi. from the set, and the intervening circuit will consist of a 4-conductor, No. 14 twisted pair circuit (or 2-conductor at option of manufacturer). Proposition shall include transmitting and receiving equipment, selective ringing equipment at set and at operator's station, telephone equipment at set and operator's station, motor-generator sets, and all other accessories necessary to complete and satisfactory operation of set. This set shall have sufficient range to communicate with Mitchell Dam and with Meridian under all conditions. Operation through open disconnecting switches is not contemplated, but set should be able to function satisfactorily, even with one conductor grounded. Power Company will furnish necessary storage batteries.

Line Equipment. For use along the line between Mitchell Dam and Demopolis, control equipment shall be provided for five sectionalizing switches. Power supply at each of these locations will be from 12-volt, 120-ampere hour storage batteries, to be provided by the Power Company, the voltage of which may fluctuate between 10 and 15 volts. These equipments shall include receiving apparatus, and any protective equipment which may be recommended. The sectionalizing switches which these devices will control will be motor operated, and will require approximately 20 seconds to open or close.

Drainage and protective equipment shall be provided for the insulated overhead ground wire previously described, for eight locations, this equipment to be ample for protecting these conductors and the control equipment connected to them, from excessive voltages incidental to line failures of any sort. These equipments, in general, shall include an iron core choke, a spark-gap, and a quick acting relay inserted in the connection from the middle of the choke to ground, which will act to provide a direct path to ground for both conductors in case of an excessive discharge through the choke to ground. These devices shall also be such that they will not interfere with the use of these conductors for telephone communication in emergencies when the adjacent power circuit is "dead." This equipment shall be compact, weatherproof, and suitable for mounting on standard line structures.

Equipment shall be provided for charging 12-volt batteries at five locations as previously referred to, utilizing drainage from the insulated overhead ground wire or from separate antennas strung parallel to the conductors. This equipment should be suitable for a continuous (or trickle) charge, and should include any necessary safety or protective equipment.

All of the above drainage and protective equipment should be specified with the idea of taking care of any ordinary line faults, and any conditions which are apt to be encountered incidental to the ordinary operation of the power circuit, or to any ordinary faults which may develop in same. All equipment must be sturdy and suitable for outdoor installation. It should be noted that in case of short circuits from conductor to ground, the ground currents will probably vary between 500 and 1000 amperes, but may ultimately go as high as 2500 amperes for the portion of the lines adjacent to Lock 18.

Control equipment,—receiving or return signal,—shall be of such nature as not to depend on vacuum tube equipment requiring continuously lighted filaments for correct operation, except that such devices may be used in the visual return signal equipment at Mitchell Dam.

In the case of the above equipment, all items shall be suitable for complete and satisfactory operation under the conditions outlined and described, and shall include all accessories necessary for their operation and protection, and for reasonable safety of operators.

Discussion

For discussion of this paper see page 236.

The Transmission of High-Frequency Currents for Communication over Existing Power Networks

BY C. A. BODDIE[1] and R. C. CURTIS[1]
Associate, A. I. E. E. Non-member

Synopsis.—The use of high-voltage power lines for carrier-current communication presents a number of difficulties not met in the use of simple communication circuits. This paper tells how these difficulties may be overcome without resorting to complicated transmitting and receiving equipment. The advantages of employing tuned choke coils are described. These chokes are used to isolate the communication channel from the remainder of the power system which gives in effect a simple communication circuit between communicating points.

* * * * *

HIGH-voltage power lines are constructed with such strength that they are in general superior to any communication circuit except underground cable. Experience has demonstrated that power lines withstand storms, sleet, and floods long after all other circuits are carried away. In view of the vital necessity of communication to a power company, it is but natural that the power line should be used as a communication circuit because of its mechanical superiority. Except for short distances, it also offers an economic superiority.

The method of utilizing a power line as a telephone circuit is to superimpose high-frequency currents on the power conductors. These currents are transmitted over the line as ordinary alternating currents. They are produced and received by equipment similar to the usual space radio apparatus.

In considering the power line as a communication circuit it is immediately apparent that such a circuit differs from the usual telephone line. The principal difference is that the line is operated at high voltage. This gives rise to more or less noise due to spitting insulators and similar effects. In addition the line is not a simple circuit connecting the transmitter and receiver. In practise a power line is usually part of an extensive high-voltage network with loops, taps, and spurs. Such a network is not a constant and stable system from a communication point of view because of more or less continuous changes due to switching. In general, every time a switch is opened or closed in any part of the system, it makes a change in the communication circuit.

These factors are now generally recognized although at the time this type of communication was first undertaken, the importance of some of them was not fully appreciated. In some cases it was found that the natural changes in line characteristics due to switching were so great that a satisfactory communication circuit could not be obtained.

Efforts have been made to solve this problem by modifying the communication apparatus. Modifications tending to reduce the number of frequencies per channel and the introduction of special systems of modulation have greatly increased the amount and complexity of the equipment.

By its very nature power line communication equipment should be kept just as simple and reliable as possible. Instead of complicating the equipment it is proposed to correct the trouble at its source by stabilizing the power line. The method is to insert high-frequency resistances into the power line at such points as are necessary to block off detrimental circuits and provide a clear circuit for the channel desired.

Apparatus for this purpose has been developed which has proved simple and effective. This apparatus consists of an inductance coil very similar to those ordinarily used for lightning arrester work together with the necessary tuning equipment. These tuned circuits do not absorb energy at the power frequencies nor in any way disturb the power system.

In order to appreciate the problem presented by a power network some of the properties of transmission lines at high frequencies may be noted.

A line of great length does not act like a large capacity or a large inductance but rather as a pure resistance of approximately 800 to 850 ohms for the average power line construction. The impedance of a short line open at the end varies over a wide range.

A representative type of construction is shown in Fig. 1 with the high-frequency currents superimposed between conductors "1" and "3." The attenuation ratio, that is the ratio of the current or voltage received at the distant end to that impressed at the sending end for the type of construction assumed, is shown in Fig. 2. It is interesting to note that the losses in a simple circuit are not serious. For example, the current delivered by a line 100 mi. long is 40 per cent of that transmitted. A 200-mi. line delivers 16 per cent and a 300-mi. line about 6 per cent of the transmitted current.

In Fig. 3 is shown a type of power system in which the branch lines are all of considerable length. The impedance of such branch lines when long is approximately the characteristic impedance. Suppose it is desired to provide a communication channel between *A* and *F*, it is seen by inspection that 50 per cent of the

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[1] Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

Presented at the Regional Meeting of the Southern District of the A. I. E. E., Atlanta, Ga., Oct. 29-31, 1928.

current fed into the system at *A* is transmitted towards *B*. The part transmitted in the opposite direction is lost since it contributes nothing to the desired channel *A–F*.

When a wave reaches a junction of two long lines a division of current takes place such that ⅓ of the original current is reflected back towards the sending end while ⅔ is transmitted down each branch line, the total being ⅓ greater than the original.

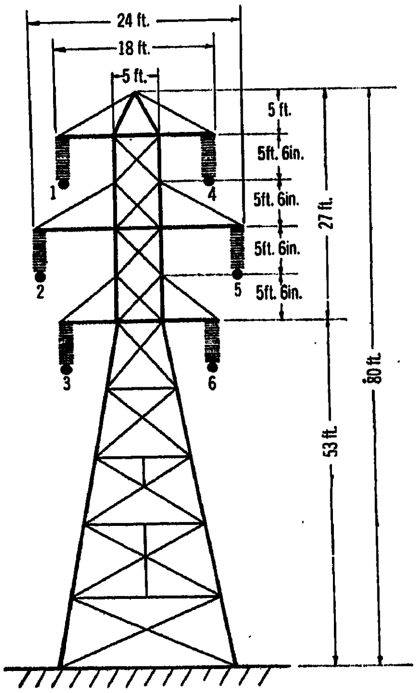

Fig. 1—Typical Line Construction

Hence, the wave transmitted from *A* reaching the junction point *B* divides, ⅔ of the current being transmitted toward *C*, the rest being lost. Neglecting the transmission loss in the line, ⅓ of the original is transmitted towards *C*. At *C* a similar division takes place leaving 2/9 to be transmitted to *E*. At *E* ⅔ of the arriving current that is 4/27 of the original is transmitted into the pair of lines towards *F*. Since only one of these lines continues to *F*, ½ of this or 2/27 is transmitted to *F* as useful current.

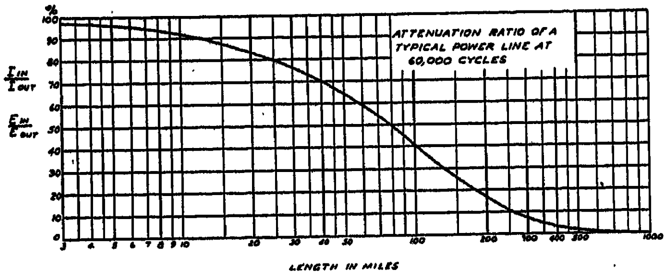

Fig. 2—Attenuation Ratio of a Typical Power Line at 60,000 Cycles

The net effect of the subdivision of current at the junction points is the same as the attenuation of slightly less than 300 mi. of simple circuit, as seen from Fig. 2. In addition there is the loss due to the normal attenuation in the line.

Consider the case shown in Fig. 4 of a long line with a 4-mi. spur line connected on at *B*. The impedance of the 4-mi. spur line at frequencies commonly used is shown in Fig. 5. The impedance of the spur line at 58.1 kilocycles is so low that less than 4.5 per cent of the current arriving at *B* is transmitted down the line towards the receiving apparatus at *C*. The effect of such a spur line is equivalent to the loss incurred in a line of over 300 mi. in length. It should be noted that at certain frequencies the effect of a single short spur line is greater than that due to the many subdivisions shown in Fig. 3.

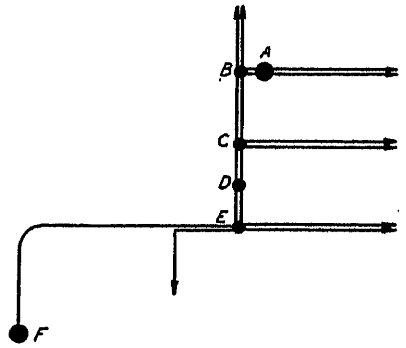

Fig. 3—Power System with Branch Lines

At other frequencies the impedance of the spur line is very high and at these points has little or no effect on the transmission of energy from *A* to *C*. The frequencies at which these points of maximum and minimum transmission occur are a function of the length of the spur line. If a number of such spur lines of varying length is connected to the main line it may be impossible to find a single frequency that will be satisfactory for communication.

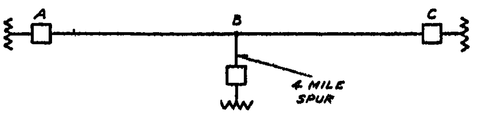

Fig. 4—Power System with a Spur Line

A set of resonant line chokes may be installed in the spur line at the point where it connects to the main line. The minimum effective impedance of the spur line can thus be raised and the diversion of energy reduced to any desired amount.

Another condition often encountered is that of two or more parallel paths of slightly different lengths. At certain frequencies the current arriving by one path is exactly out of phase with the current arriving by the other. If the paths are of nearly equal length the amplitudes of the arriving currents will be very nearly equal. The two will then combine in such a way as nearly to cancel each other, leaving only a very small resultant to act on the receiver.

This condition may be corrected by inserting a set of resonant line chokes in one of the lines to prevent the flow of current by that path. Sometimes this procedure is objectionable because either of the lines may be opened during the normal operation of the system.

By inserting reactances at one or more points along the line the phase of the currents arriving at the receiving end can be shifted so that the resultant acting on the receiver is an appreciable portion of that delivered to the receiving end of the line. The construction of these phase shifting reactors is similar to the resonant line chokes. The tuning of the circuit is such as to present a reactance of the required value. In this way use is made of both the available paths. The opening or failure of one of the lines does not materially affect the communication channel.

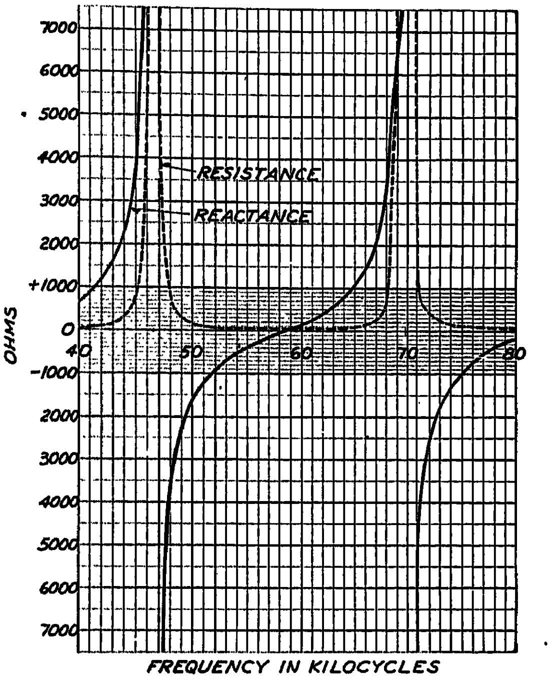

FIG. 5—RESISTANCE AND REACTANCE OF A FOUR-MILE SPUR LINE

In Fig. 6 is shown another condition met in practise in which F is energized either by way of C and D or by E. The loop is not maintained closed in normal operation of the power system. The communication channel is from A to F.

If the loop is opened at C, D, or E the effect is that of two spur lines connected across the communication channel. If the loop is opened at B or F the effect is that of one spur line. It is necessary to provide for communication over either circuit so that high impedance line chokes cannot be used at B and F to isolate one circuit.

The corrective measures in this case consist of installing at B and F in both circuits, resonant line chokes adjusted to an impedance such that a considerable amount of current can pass through the circuit to F. At the same time the impedance is high enough to prevent an excessive amount of current flowing when the circuit becomes part of a spur.

The impedance of some types of transformers is quite low at high frequencies. Other types have been encountered in which the impedance varies with the instantaneous values of the power current giving the effect of modulation on the high-frequency currents. These conditions may be remedied by the use of the resonant line choke to prevent any appreciable amount of high-frequency energy being absorbed in the undesirable circuits.

Power lines are now being studied very carefully before any attempt is made to install power line telephone equipment. Actual tests have demonstrated the validity of the commonly accepted theory of lines for high frequencies. By applying accepted analytical methods, the important features of the line characteristics may be determined. If these are found to be unsatisfactory, corrective impedances are inserted at such points as will give the desired results.

THE PROPAGATION OF HIGH-FREQUENCY CURRENTS ON POWER LINES

The fundamental properties of lines at high frequencies may be best understood by first considering a line of infinite length, since no energy is reflected back toward the sending end to combine and interfere with the advancing wave. The amplitude of the voltage vector is progressively reduced as it travels away from the sending end. The magnitude of the voltage vector at a point x is expressed by

$$E_x = E_0\, \epsilon^{-\alpha x} \qquad (1)$$

where α is the attenuation constant.

The phase position of the voltage vector is shifted backwards as the distance from the sending end increases. The position is given by the equation:

$$E_x = E_0\, \epsilon^{-j\beta x} \qquad (2)$$

where β is the wavelength constant. It is the number of radians per mile which the voltage vector is shifted backwards. This action is shown graphically in Fig. 7.

The complete expression for the voltage at any point x along an infinite line is then,

$$E_x = E_0\, \epsilon^{-x(\alpha + j\beta)} = E_0\, \epsilon^{-Px} \qquad (3)$$

where P is the propagation constant and is equal to $(\alpha + j\,\beta)$.

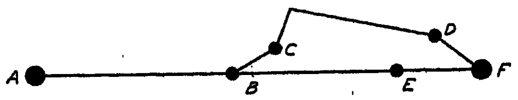

FIG. 6—POWER SYSTEM WITH LOOP

The propagation constant may also be expressed in terms of the fundamental line constants per unit length.

$$P = \sqrt{R + j\,\omega L}\ \sqrt{G + j\,\omega C} \qquad (4)$$

where R is the resistance in ohms.
L the inductance in henrys.
G the leakage conductance in mhos
C the capacity in farads.

The vector impedance of an infinite line measured at the sending end is known as the characteristic impedance and may be demonstrated to be,

$$Z_0 = \frac{\sqrt{R + j\,\omega\,L}}{\sqrt{G + j\,\omega\,C}} \tag{5}$$

For a power line the R and G terms at high frequencies are negligible as compared to the reactive components. The characteristic impedance is therefore a pure resistance,

$$Z_0 = \sqrt{\frac{L}{C}} = 276 \log_{10} \frac{2\,D}{d} \tag{6}$$

where D is the distance between conductors and d the diameter of the conductor.

The values of α and β are more readily calculated from the following:

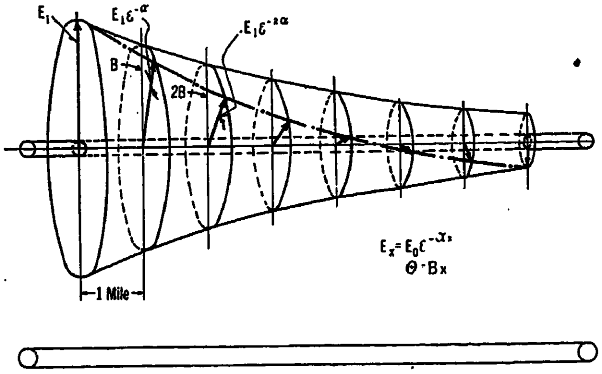

FIG. 7—DIAGRAM SHOWING THE PHASE AND MAGNITUDE OF POTENTIAL AT VARIOUS POINTS ALONG A LINE

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} \tag{7}$$

As stated above the leakage for a power line is negligible. The second term of equation (7) drops out and the expression becomes,

$$\alpha = \frac{R}{2}\,\frac{1}{Z_0} \tag{8}$$

where

$$Z_0 = \sqrt{\frac{L}{C}} \tag{9}$$

The value of the wavelength constant can be obtained from the relation:

$$\beta = \frac{2\,\pi\,f}{V} = \frac{2\,\pi\,f}{186{,}000} \tag{10}$$

The velocity of propagation is nearly equal to the velocity of light since the resistance and leakage conductance are necessarily small as compared to the reactive components. The value of the wavelength constant obtained from equation (4) for the propagation constant by neglecting R and G is

$$\beta = 2\,\pi\,f\,\sqrt{L.\,C.} \tag{11}$$

Substituting this value in the equation for velocity

$$V = \frac{2\,\pi\,f}{\beta} = \frac{1}{\sqrt{L\,C}} = 186{,}000 \text{ mi. per sec.} \tag{12}$$

The impedance of an infinite line measured at the sending end is the characteristic impedance as defined by equation (5). This is also the impedance of a finite line of any length terminated in its characteristic impedance. If the line is not terminated in its characteristic impedance the relations are much more complex. The sending end impedance for the general case of a line terminated in an impedance Z_R is:

$$Z_1 = Z_0\,\frac{Z_R \cosh P\,l + Z_0 \sinh P\,l}{Z_0 \cosh P\,l + Z_R \sinh P\,l}$$

$$= Z_0\,\frac{Z_R + Z_0 \tanh P\,l}{Z_0 + Z_R \tanh P\,l} \tag{13}$$

For a line short-circuited at the receiving end Equation (13) reduces to,

$$Z_1 = Z_0 \operatorname{Tanh} P\,l \tag{14}$$

For a line open at the receiving end

$$Z_1 = \frac{Z_0}{\operatorname{Tanh} P\,l} \tag{15}$$

Equation (15) is of particular interest since the power network quite often consists of spur lines tapped off the main line which is to be used for a communication channel. The effect of such spur lines is generally quite serious. Equation (15) may be further expanded to give both the resistance and reactance components.

$$Z_1 = Z_0\,\frac{\tanh \alpha\,l\,(1 + \tan^2 \beta\,l)}{\tanh^2 \alpha\,l + \tan^2 \beta\,l}$$

$$- j\,Z_0\,\frac{\tan \beta\,l\,(1 - \tanh^2 \alpha\,l)}{\tanh^2 \alpha\,l + \tan^2 \beta\,l} \tag{16}$$

By an inspection of Equation (16) it is seen that the reactive component goes through zero every 90 deg. and at the odd quadrants the resistance term becomes,

$$Z_1 = Z_0 \tanh \alpha\,l \tag{17}$$

At the even quadrants

$$Z_1 = \frac{Z_0}{\tanh \alpha\,l} \tag{18}$$

Between the points of maximum and minimum resistance the reactive component predominates unless the value of $\alpha\,l$ is large. The value of the $\tanh \alpha\,l$ is always less than unity so that points of minimum impedance occur at the odd quadrants, that is whenever the value of $\beta\,l$ is such that the tangent of $\beta\,l$ is infinite. This occurs at all the odd multiples of 90 deg. or $\frac{\pi}{2}$ radians. The points of maximum impedance occur at all values which make the tangent of $\beta\,l$ equal to zero or at all the even multiples of 90 deg.

The interval between the maximum and minimum values may be determined by referring to Equation (10)

$$\beta\, l = \frac{2\,\pi f\, l}{V} = \frac{\pi}{2} \text{ for first minimum value}$$

$$f = \frac{\pi}{2}\left(\frac{V}{2\,\pi\, l}\right) = \frac{V}{4\, l} = 4.65 \times 10^4 \times \frac{1}{l} \quad \textbf{(19)}$$

The presence of a transformer bank and other power apparatus terminating the spur line further complicates the problem of obtaining a satisfactory communication channel. The effect may be calculated from Equation (**13**), if the impedance of the apparatus is known.

Another method giving a better insight into the problem is to replace the terminal apparatus by a line of such length that its impedance is the same as the apparatus replaced. This equivalent line may be either open or short. If an open line is used it merely adds to the original line and the effects become more evident. The impedance of an open line is given by Equation (**15**). The length of the equivalent line must then be such that,

$$\tanh \theta_R = \frac{Z_0}{Z_R} \quad \textbf{(20)}$$

The sending end impedance of the line with its terminal apparatus is then the same as the original line plus the equivalent line or,

$$Z_1 = \frac{Z_0}{\tanh(\theta + \theta_R)} \quad \textbf{(21)}$$

Expanding Equation (**21**) into its real and imaginary components gives,

$$Z_1 = Z_0 \frac{\tanh(\alpha\, l + \alpha_R)\,[1 + \tan^2(\beta\, l + \beta_R)]}{\tanh^2(\alpha\, l + \alpha_R) + \tan^2(\beta\, l + \beta_R)}$$

$$- j\, Z_0 \frac{\tan(\beta\, l + \beta_R)\,[1 - \tanh^2(\alpha\, l + \alpha_R)]}{\tanh^2(\alpha\, l + \alpha_R) + \tan^2(\beta\, l + \beta_R)}$$

This equation is of the same form as Equation (**16**). It differs in that the real and imaginary components of the propagation constant applying to the line are increased by the components corresponding to θ_R of the transformer bank. By comparison with Equation (**16**) it will be seen that the maximum value of impedance is reduced and the minimum increased. Tests on transformers indicate that the impedance is principally a capacity reactance. If the impedance of the transformer bank remains substantially constant over the range considered, the number of cycles between peaks on the impedance curve of the spur line is the same as for the line without the transformer bank. The net effect of a transformer bank on this assumption is to shift the whole impedance curve such as Fig. 5 down in frequency without changing the distance between peaks. In practise it is found that the impedance of the transformer is not constant. The transformers therefore make the observed impedance curves differ from the simple case.

APPLICATION TO A TYPICAL LINE

The application of the foregoing equations may be seen by considering a typical line such as shown in Fig. 1. The conductors are assumed to be 4/0 stranded copper with a spacing of 22 ft. between the outside conductors.

The d-c. resistance per loop mile is 0.518 ohms. The high-frequency resistance may be calculated by the method given in Circular 74 of the Bureau of Standards. The ratio of the high-frequency resistance to the d-c. resistance is obtained from a table giving values of a factor X_c. The value of X_c varies directly with the diameter and the square root of the frequency. The equivalent diameter of a stranded wire is assumed to be equal to the diameter of a solid wire having the same copper cross-section. The data in this table are plotted in the form of a curve in Fig. 8. The high-frequency resistance calculated by this method for 4/0 stranded copper at 50,000 cycles is 10.5 times the d-c. resistance or 5.44 ohms.

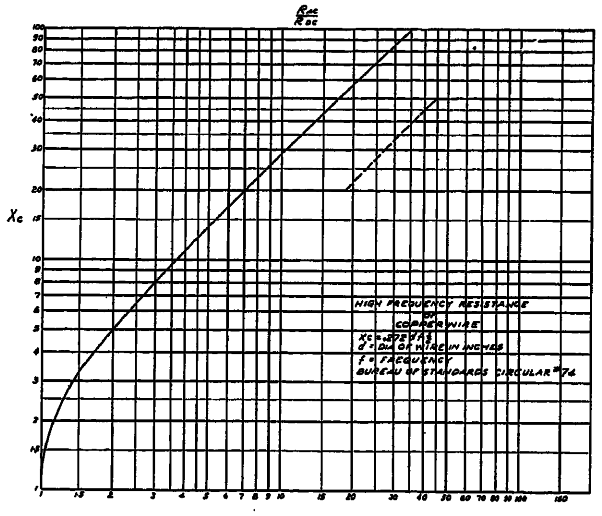

FIG. 8—HIGH-FREQUENCY RESISTANCE OF COPPER WIRE

Measurements on a number of lines of this general type indicate that the actual line resistance (due to losses not understood at present) is approximately 250 per cent of the value calculated. The dotted curve shown on Fig. 8 will therefore be used. This gives a value of 13.6 ohms per loop mile at 50,000 cycles for the 4/0 stranded copper conductor.

It will be here assumed that over the range of frequencies being considered the high-frequency resistance varies as the square root of the frequency, and that the tabular values should be multiplied by a factor of 2.5. Values so calculated check closely with observed results.

The inductance per loop mile may be calculated from the formula,

$$L = 1.48 \times 10^{-3} \log_{10} \frac{2\, D}{d} \text{ henrys} \quad \textbf{(23)}$$

where D is the distance between conductors, d is the diameter of the conductor. The value for the typical case assumed above is,

$$L = 1.48 \times 10^{-3} \log_{10} \frac{2 \times 12 \times 22}{0.538} = (148 \times 10^{-3})$$

$$\times\ (2.992) = 4.43 \times 10^{-3} \text{ henrys per loop mile.}$$

The capacity between wires per mile may be calculated from the formula,

$$C = \frac{0.0194}{\log \dfrac{2D}{d}} \times 10^{-6} \text{ farads}$$

$$= \frac{0.0194}{2.992} \times 10^{-6}$$

$$= 0.065 \times 10^{-6} \text{ farads} \qquad (24)$$

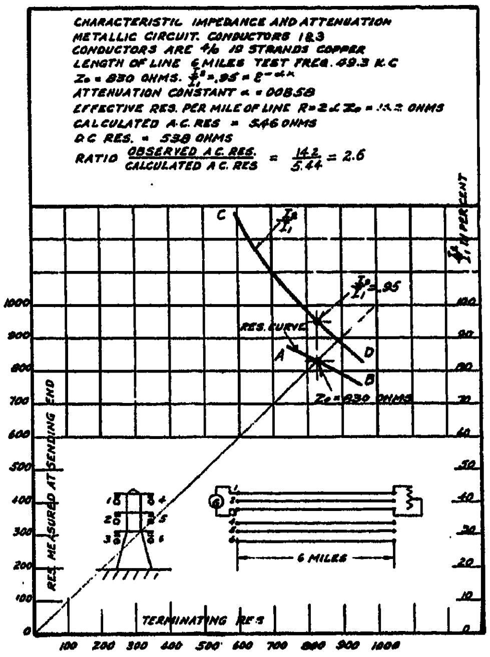

FIG. 9—CHARACTERISTIC IMPEDANCE AND ATTENUATION

The propagation constant obtained from Equation (4) assuming $f = 50{,}000$ cycles is

$$P = \sqrt{13.6 + j\,1390}\ \sqrt{0 + j\,2.04 \times 10^{-3}}$$

$$= 1.69 \,\underline{/\ 89^\circ\ 43.2'}$$

$$= 0.00826 + 1.69 = \alpha + j\,\beta$$

The value of the attenuation constant calculated from Equation (8) is

$$\alpha = \frac{R}{2}\,\frac{1}{Z_0} = \frac{13.6}{2}\,\frac{1}{825} = 0.00825$$

Where Z_0 from Equation (9) is 825 ohms.

The value of the wavelength constant calculated from Equation (10) is

$$\beta = \frac{2\,\pi f}{v} = \frac{(2\,\pi)\,(50{,}000)}{186{,}000} = 1.69$$

MEASUREMENT OF CHARACTERISTIC IMPEDANCE

The characteristic impedance is known to be a resistance from Equation (6). As stated above the characteristic impedance is measured at the sending end of a finite line when the receiving end is terminated in the characteristic impedance. Trial values of resistance are inserted at the receiving end and the resistance measured at the sending end. These values are plotted in the form of a curve *A-B* as shown in Fig. 9. The measured value in this case is 830 ohms which agrees well with the calculated value of 825 ohms.

In taking the data for determining the characteristic impedance, ammeters are inserted at the sending and receiving ends as shown in Fig. 10. The ratio of the receiving end current to the sending end current is plotted in the form of a curve *C-D* for various values of terminating resistance. The attenuation ratio is then easily determined for the particular value of resistance that is found to be equal to the characteristic impedance.

MEASUREMENT OF LINE RESISTANCE

The data shown in Fig. 9 were taken on a 6-mi. line constructed as shown in Fig. 1. The attenuation ratio is 95 per cent. The attenuation constant is

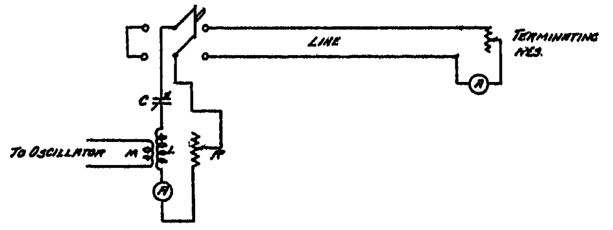

FIG. 10—APPARATUS AND CIRCUIT USED IN MAKING LINE MEASUREMENTS

$$E^{-\alpha l} = \frac{I_2}{I_1} = 0.95$$

$$\alpha\, l = 0.0515$$

$$\alpha = 0.00858$$

The effective resistance per mile of line obtained from Equation (8) is,

$$R = 2\,\alpha\, Z_0$$

$$= 14.2 \text{ ohms}$$

$$\text{Ratio } \frac{\text{Observed A-C. Res.}}{\text{Calculated A-C. Res.}} = \frac{14.2}{5.4} = 2.63$$

Values obtained by test on other lines vary between 2.0 and 3.0, the value 2.5 used in these calculations being a fair average.

SPUR LINES

Fig. 5 shows the variation of impedance of a typical 4-mi. spur between 40 and 80 kilocycles. The reactance curve is seen to be a typical tangent curve except for the higher values. The reactance curve reaches a maximum and then passes through zero instead of following the tangent curve to infinity. This is also evident from an inspection of Equation (**16**) since the values of $\tanh^2 \alpha l$ are small as compared to unity and small as compared to most values of $\tan^2 B l$.

The impedance presented by a 4-mi. spur varies over a wide range. The impedance at 46.5 kilocycles is 26,000 ohms and at 58.1 kilocycles 29.3 ohms. The impedance then rises again to a maximum of 21,200 ohms at 69.7 kilocycles. The interval between the points of maximum and minimum impedance as given by Equation (**19**) is

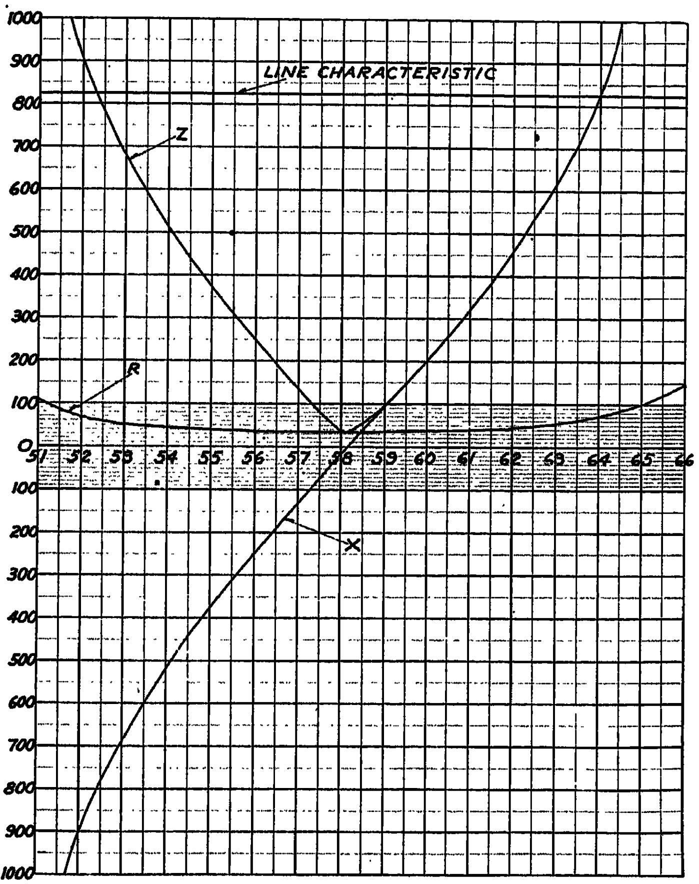

FIG. 11—ENLARGED SECTION OF FIG. 5

$$\frac{V}{4\,l} = \frac{186{,}000}{4 \times 4} = 11{,}600 \text{ cycles}$$

It should also be noted that the impedance between 52.5 kilocycles and 63.7 kilocycles is less than the characteristic impedance of the line and will in this band of frequencies absorb considerable energy in addition to the loss in the main line due to reflections. Fig. 11 shows an enlarged portion of the curve in Fig. 5. The presence of a single 4-mi. spur line tapped on the main line causes over 50 per cent of the available high-frequency channels to be subject to wide variations in signal level by switching conditions. If several such spur lines of varying lengths are present, it may be impossible to find a single frequency which will not be subject to excessive attenuation and variation with changes in the operating condition of the power system.

The presence of a transformer bank at the end of the spur line adds further complications. Switching the bank on and off changes the frequencies at which the points of maximum and minimum impedance occur.

For example, if the 4-mi. spur line were terminated in a large substation having a number of transformer banks connected in parallel, the points of maximum and minimum impedance might be lowered as much as 5.5 to 6 kilocycles. In general the shift is of the order of 10 to 15 per cent of the interval between the maximum and minimum values as calculated by Equation (**19**).

Most transformer banks act as a capacity reactance of a rather high order. Values of 4000 ohms reactance and 200 ohms of resistance are typical. From Equation (**20**) the value of the equivalent line angle θ_R is

$$\operatorname{Tanh} \theta_R = \frac{Z_0}{Z_R} = \frac{825 \,\underline{/\,0^\circ}}{4000 \,\overline{\backslash 87.2^\circ}} = 0.206 \,\underline{/\,87.2^\circ}$$

$$\begin{aligned} \theta_R &= 0.206 \,\underline{/\,87.2^\circ} \\ &= 0.01007 + j\,0.206 \\ \alpha_R &= 0.01007 \\ \beta_R &= 0.206 \text{ radians} = 11.8^\circ \end{aligned}$$

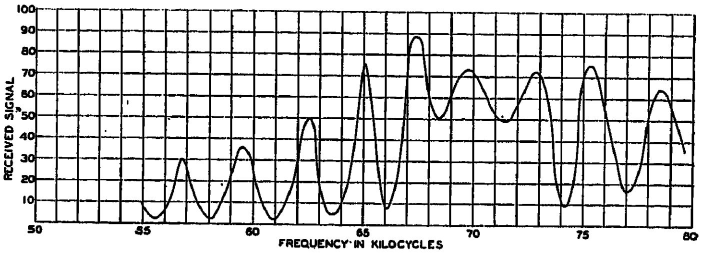

FIG. 12—RECEIVED SIGNAL FOR 50- TO 80-KILOCYCLE BAND

Showing the effect of a spur line, approximately 34-mi. long at the receiving end

Substituting these values in Equation (**21**) lowers the point of maximum impedance from 26,000 ohms at 46.5 kilocycles to 20,000 ohms at 44.98 kilocycles. Similarly the point of minimum impedance is changed from 29.4 ohms at 58.1 kilocycles to 37.3 ohms at 56.58 kilocycles.

The energy absorbed by a spur line becomes more nearly constant as its length increases. Also as the length increases the interval in cycles between maximum and minimum values becomes less. The actual loss of energy in the case of a long spur line is not such a serious factor. The rapid variation of impedance does, however, cause considerable distortion of the modulated wave. In Fig. 12 are shown the results of a test made on a portion of a typical power system. The most noticeable feature is the rapid fluctuation of signal with frequency. This is due to the location of the receiver at a point approximately 34 mi. from the end of the line.

Increasing the attenuation either by raising the frequency or by increasing the length will tend to limit the variation of impedance. The impedance approaches the characteristic impedance as a limit as the length becomes great. The maximum and minimum values of impedance for varying values of the attenuation factor are plotted in the form of a curve in Fig. 13. It should be noted that a value of the attenuation factor of 0.55 or greater is required to prevent the minimum values of the spur line impedance from falling below 50 per cent of the characteristic impedance value. This would require the spur line to be at least 66.7 mi. long assuming the frequency to be 50 kilocycles and the type of construction as shown in Fig. 1. At 100 kilocycles the required length is only reduced to 47 mi.

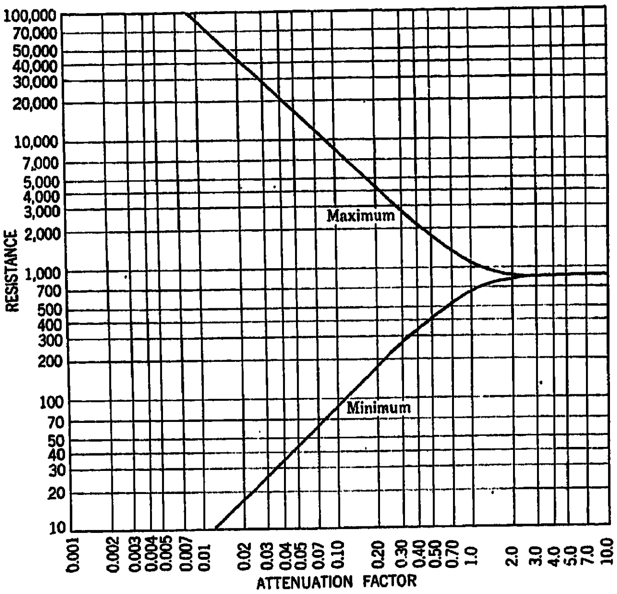

Fig. 13—Maximum and Minimum Values of Spur Line Impedance

From the foregoing it is apparent that the effect of spur lines is very detrimental. The short lines cause excessive transmission loss over wide bands of frequencies and the longer lines cause distortion due to the rapid variation of impedance with frequency. All types of telephone communication utilizing high-frequency currents require the transmission of a band of frequencies rather than a single frequency. The width of the band may be reduced to some extent by employing special types of modulation. The best that can be accomplished in this direction will not reduce the width of the band below 2000 cycles. This gives only a minor improvement without providing a general solution to the problem.

The detrimental effects of spur lines may be obviated by making certain changes in the transmission system. Any desired frequency can then be used, distortion is eliminated, wide fluctuations in signal level are prevented, and complications in the transmitting and receiving apparatus are avoided.

These results can be accomplished by inserting in the power conductors, equipment which will carry the power current without loss and at the same time introduce high impedances to the communication currents.

Resonant Line Chokes

Physically the resonant line chokes are dividing into two classes. The single layer type is used for introducing moderate amounts of resistance into the power line and the double layer type for introducing a high resistance to isolate an undesirable circuit. The single layer resonant line choke consists of an inductance coil similar to a standard lightning arrester choke and the necessary tuning equipment. The double layer type is similar except that the number of turns on the inductance coil has been doubled by the addition of another layer of winding as shown in Fig. 14.

The tuning equipment is shown in Fig. 15. The diagram of connections is given in Fig. 16. The condenser C_1 is used to tune the main inductance coil L_1 to the frequency it is desired to obstruct. An additional tuned circuit L_2, C_2 coupled to the main coil L_1. It also contains an adjustable resistance R_2. The function of the second circuit is to broaden the resonance curve so as not to injure modulation. By tightly coupling the second circuit to the first, the system is made to tune to two frequencies. In this way a single choke can be made to block two frequency bands. By varying the adjustment of this circuit the impedance presented by the choke can be changed from a high impedance over a narrow band of frequencies to a moderate impedance over a wide band of frequencies.

A typical impedance curve for the double layer type of choke is shown in Fig. 17. Chokes are placed in each of the line conductors so that the total line-to-line impedance is of the order of 12,000 ohms as compared to the line characteristic impedance of 825 ohms. It is evident that a circuit isolated by this type of choke cannot divert any appreciable amount of the communication current.

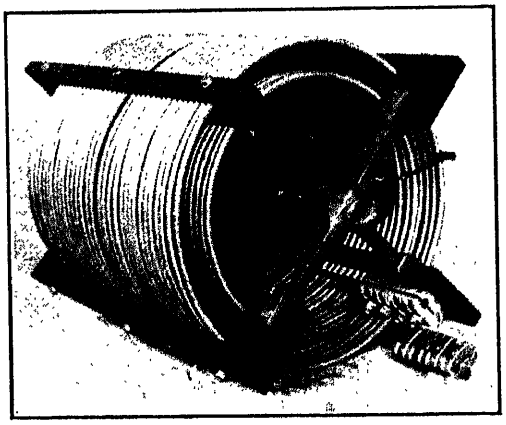

Fig. 14—Double Layer Resonant Line Choke

In Fig. 18, curve No. 1 shows the resistance curve of a single layer choke adjusted to give a moderately high resistance at two frequencies. By the use of this type two channels can be cleared. A resistance of approximately 400 ohms per choke is sufficient to limit the current in an undesirable circuit to a value that will not seriously affect the communication channel.

The adjustment may be changed so as to give a very flat impedance curve as shown in curve 2, Fig. 18. This is a very valuable characteristic, and is used where it is necessary to stabilize a power system and still transmit through the chokes as in the case shown in Fig. 6.

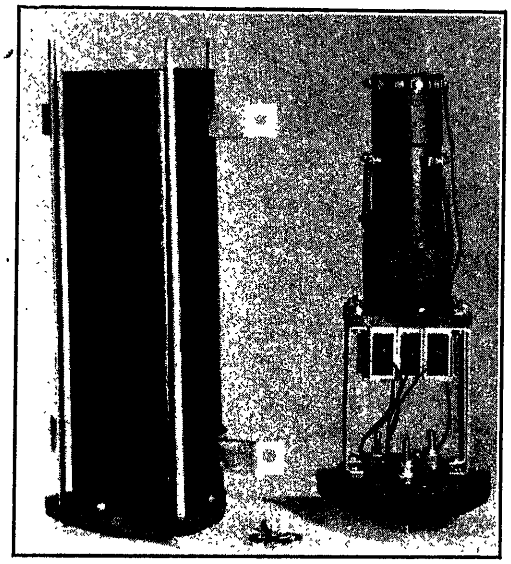

Fig. 15—Tuning Equipment for Resonant Line Choke

Conclusion

The ideal condition for a high-frequency telephone system is to have the line a simple circuit directly connecting the points between which communication is required. This ideal may be approximated as closely as desired by isolating the channel from the rest of the power system. This is made possible by the installation of resonant line chokes at appropriate points.

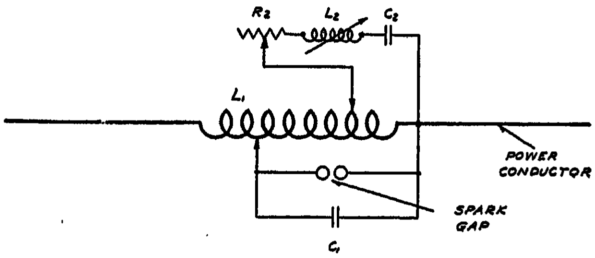

Fig. 16—Diagram of Connections for Resonant Line Chokes

Some of the advantages gained are:

1. Increased stability.
2. Improved quality of speech transmitted.
3. Reduction in the noise level due to the greater energy delivered to the receiver.
4. Freedom from variation in signal due to switching.
5. Simple transmitting and receiving equipment satisfactory on complex systems.
6. Increased reliability.
7. Ability to transmit through practically any type of system.
8. Ability to utilize all lines between communication points.

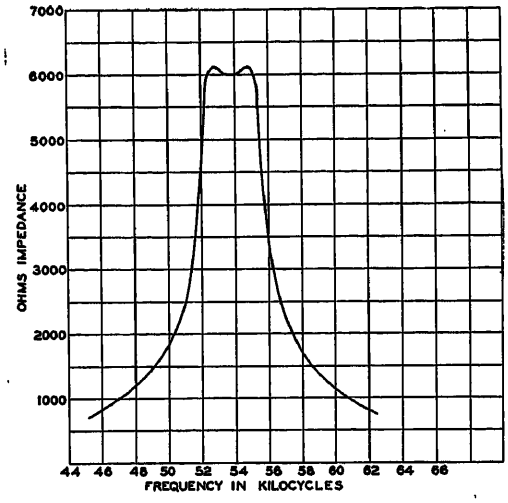

Fig. 17—Typical Impedance Curve for a Resonant Line Choke, Double Layer Type

9. Interference with equipment on adjacent power systems can be eliminated.
10. Reduction in field work at the time of installation.

The application of the established line theory to the analysis of power lines has materially advanced the art of telephone communication over power lines. It is now possible to predict with reasonable accuracy what frequencies can be successfully transmitted over a given power network. This materially reduces the extensive field work which has often been necessary when making an installation. If the analysis shows that there are conditions which prevent the use of the desired frequency bands, corrective measures may be taken by installing resonant line chokes at suitable points. System limitations are largely overcome by this procedure and the field of application of high-frequency communication materially increased.

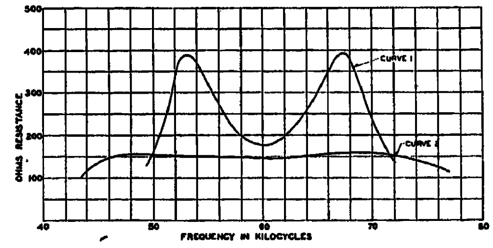

Fig. 18—Typical Resistance Curves for Resonant Line Chokes, Single Layer Type

Discussion

CARRIER-CURRENT AND SUPERVISORY CONTROL ON ALABAMA POWER COMPANY'S SYSTEM

(Robinson and Woodcock)

LINE CHARACTERISTICS FOR CARRIER COMMUNICATION

(Boddie and Curtis)

C. F. Boeck: The authors say that power-line carrier equipment should be as simple and reliable as possible. I agree that simplicity of terminal arrangement and in the configuration of the power network are desirable features. It is unusual, however, for any complex problem which involves contradictory factors to be solved by simple and direct methods alone or by the direct application of simple methods to any one factor. In the early days of power-line carrier telephony, it was thought that the power line would have a rather smooth and stable high-frequency transmission characteristic. Simple terminal equipment was therefore proposed with the idea of using ample power to over-ride the variations in the transmission line. Later it became evident that the transmission line did not have a stable high-frequency characteristic and that it was subject to variations due to switching operations and other changes in the line. The problem is still in the process of solution and it will probably be some time before the various factors involved are properly coordinated. I wish to suggest, therefore, that perhaps the emphasis should be placed upon reliable rather than simple terminal equipment and that the terminal equipment should be as simple as is consistent with reliability.

Power-line carrier telephone equipment initially was designed to use the transmission line without modification for a communication channel. The development, therefore, has been centered largely upon terminal apparatus and has resulted in the development by us of single-frequency duplex, single-sideband, carrier-suppressed equipment which was discussed at a recent Institute meeting.[1]

This equipment represents a distinct advance in the art and is giving reliable service over a complex power distribution network. It was installed after two years' experience with other terminal equipment had fully demonstrated its inability to meet the conditions imposed by this particular network.

Full advantage of improvements in terminal apparatus cannot be realized unless the transmission characteristics of the power line are favorable. The authors propose to improve the transmission characteristics by the use of high-frequency choke coils inserted in the power line at suitable places to isolate the detrimental effects of branch circuits. This method is a useful one and has a certain application. It has, however, some disadvantages. The first is the design of this choke coil. That involves in advance a knowledge of the carrier frequency which you are going to use in order that you may properly tune the choke coil. It may be possible to predict this frequency with reasonably close accuracy from a study of the line by using the information which Mr. Boddie has given us. If not, it may involve a preliminary frequency survey of the line. This method, moreover, is applicable to only a narrow frequency band. Furthermore, the use of choke coils complicates the addition of future carrier channels.

In Fig. 12 of the paper, the authors show how the transmission between two points in a power line is influenced by one small tap line somewhere between them. I should like to know if they have any data showing the changes in the transmission characteristics of that line resulting from isolating the spur line by choke coils.

Another method which may have some value in eliminating reflection effects is to terminate properly the transmission lines and the spur lines. This method has an additional advantage over the use of choke coils, if it is a feasible one, in that it will provide a wider frequency band and permit the use of several channels on the power line. An investigation showing what might be accomplished by this method I think would be desirable also.

Connected power machinery also influences the transmission characteristics of a power line and leads to reflection effects. It may be possible in the future design of power machinery to give some thought to it so that its effect upon carrier transmissions will be minimized.

An additional advantage of considerable importance to the power companies may accrue by improving the high-frequency transmission characteristics of the power lines in that these improvements may reduce the magnitude and effect of line surges and switching transients. However, until such time as we can determine definitely what methods shall be used to improve the carrier-frequency characteristics of a power line, we will have to use the lines more or less as they are and to depend upon terminal equipment to help us over the rough spots.

L. E. Anderson: I wish to make a few remarks as to the inconsistencies and disadvantages of the use of power-line carrier from an operating standpoint.

One of the first things I wish to mention is the interference which results between apparatus of different manufacturers. It will be necessary for the manufacturers to get together and make apparatus that will not interfere with other apparatus. We have on our system 10 low-power sets of one manufacturer and 2 high-power of another,

When we are using the high-power equipment, all the equipment of low power is inoperative due to relays being paralyzed. We have a condition where 4 of our stations on the low-power equipment are paralyzed from one of the high-powered sets about 400 mi. away. While people are talking in Alabama, we are paralyzed and cannot talk until such time as they are through. Thus, it will be necessary for the manufacturers to do something about getting the sets to operate together, or provide some means of getting rid of this interference.

We have found that in balancing a network, it is much harder to balance the hybrid coils for the high power than it is for the low power.

In operating through open switches on the double circuits we are able to get through with 3 phases of one line and 2 of another open, but then the level is so low that we cannot operate consistently.

Mr. Boddie mentioned the trouble experienced in spur lines, that is, the shunt impedance at 50 to 60 kilocycles. What we have been up against are the frequencies above 80 kilocycles. We have found that the 110-kv. current transformers offer a high impedance to frequencies above 80 kilocycles. The only method of eliminating this is to by-pass the high side with a resistance of such value that it does not affect the metering equipment.

We are planning to install within the near future, double resonant line chokes which Mr. Boddie mentioned. These chokes are expected to eliminate the frequencies at which the high-power sets are operating and at the same time pass the frequency of the lower-powered sets.

L. G. Huggins: The method used to charge storage batteries in the supervisory controlled sectionalizing stations was briefly mentioned in Messrs. Robinson and Woodcock's paper. I believe that a little further discussion on this will be of interest.

Many of the switching stations are very remotely located. No power is available at these points for charging storage batteries. To haul these batteries in a truck to a charging station at periodic intervals would entail considerable work and expense.

A very unique scheme of charging these storage batteries from the overhead ground wire has been devised. As mentioned in the paper, this ground wire is insulated for use as a carrier channel and is grounded by means of drainage coils. A current transformer is connected between the drainage coil and ground.

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[1] *Problems in Power Line Carrier Telephony*, W. V. Wolfe and J. D. Sarros, see p. 107.

The output of the secondary of this current transformer is rectified by a standard Rectox charger and is used to "trickle charge" the batteries. This arrangement has been in service for some time with encouraging results.

This same method of obtaining small amounts of power from high-voltage lines has been tried in Europe, I understand, to furnish power to farmers and other isolated customers at points where it is not practical to install transformers. The amount of power that can be obtained in such a way is rather small and the regulation for lighting service or any variable load is so poor that the method is very limited in its application.

R. G. McCurdy: In connection with the paper by Messrs. Boddie and Curtis it may be of interest to contrast the problems of transmission of high-frequency currents over power networks with those arising in transmission over telephone circuits, particularly with reference to the desirable frequency ranges to be employed.

In telephone lines, attenuations are in general larger than on power lines and these increase rapidly with increasing frequency. Because of the large number of circuits in close proximity on a telephone pole line on which it is desired to employ carrier-current transmission, cross-talk must be controlled. In general, the cross-talk difficulties and the expense of controlling them increase rapidly with increased frequency. In the present state of the art, these difficulties fix an upper limit on the frequency which it is economical to employ, at a figure somewhat below 50,000 cycles.

On the other hand, in the power-system line, attenuations are lower and crosstalk problems are much less acute. Since the upper limit is established by line attenuation rather than by crosstalk, it is practicable to employ much higher frequencies up to the neighborhood of 200,000 cycles.

While the problems of high line attenuations and crosstalk are much less difficult in the power networks than in telephone lines, other difficulties are present which are not present in telephone lines, such as branch lines, bridged loads, and changes due to switching. The telephone system essentially consists of a large number of point-to-point circuits as contrasted with the power system which is essentially a "broadcasting" system.

Messrs. Boddie and Curtis propose to overcome this broadcasting difficulty by connecting in the undesired paths resonant chokes, thus providing a direct path between the points between which it is desired to communicate. Since the impedances of a given choke increase with increasing frequency, it is practicable for a given loss to the power currents to obtain a more effective blocking action as the frequency of the carrier current is increased. It may also be noted that as the frequency is increased the choking becomes effective over a wider band.

The paper also shows that, aside from any actual transmission losses due to these branches and changes due to switching, considerable distortion may be introduced by them in a telephone channel due to changes in the loss with frequency over the band which must be transmitted. Increase in the frequency usually decreases the variation in these losses with a change in frequency over the required band. On the whole, it appears that the more desirable frequency range for such transmission over power circuits lies above rather than below 50,000 cycles.

This difference in desirable frequency range for transmission over the two classes of circuits has marked advantages from the standpoint of coordination between them, and as a telephone man it appears to me a fortunate circumstance.

It has been necessary in carrier systems on telephone lines, in order to avoid cross-talk, to avoid large power-level differences in the same frequency range on circuits on the same pole line and to employ elaborate transposition arrangements to control the crosstalk between circuits employing the same frequency and operating at about the same power levels. This, in general, has required that amplifiers on all carrier circuits on a given pole line be installed at the same point, and that all transmission in one direction employ the lower half of the frequency range and all transmission in the opposite direction employ the other half. Thus, differences in power level in the same frequency band, even of the order of the amplification ratio in the repeaters, are avoided.

Transposition arrangements in the telephone-line carrier systems, the balance of the lines and equipment, together with the power levels employed, are such that coordination is secured with neighboring power circuits as far as the incidental components in the telephone carrier frequency range present on the power circuits. As far as a power-line carrier system is concerned, these incidental carrier-frequency components establish a noise level above which the system must operate. Consequently, cases of proximity between power-line carrier and telephone-line carrier systems operating in the same frequency range would involve increasing the effect of the power circuit on the telephone system by the level of the power-line carrier system relative to the level of these incidental frequencies. Since it is not practicable to transpose the power circuits in a way which would be effective at these frequencies or to lay out the two systems in a way to avoid the large level differences as is done within the telephone carrier systems, frequency allocation constitutes the only practical method of coordination at present available. As mentioned above, it is considered that these two ranges are naturally divided about the frequency of 50,000 cycles, this figure being the upper limit for telephone-line systems and the lower for power-line systems.

In connection with the paper by Messrs. Woodcock and Robinson, I should like to refer briefly to the use of medium frequencies for supervisory control and its effect on inductive coordination. I think it will be of interest to contrast the problem when these frequencies are superposed directly in the power circuit with that introduced by the scheme described in this paper, whereby they are put on between a pair of insulated "ground" wires. When these voice frequencies are placed directly on the power lines, it is necessary that their level be comparatively high, above the level of the harmonics on the power system. This means that when power lines and telephone lines are in proximity and coordinated in such a way that they can live happily together, with the normal magnitudes of the harmonics on the system, increasing the level by the use of these supervisory control systems will bring in new troubles. When the frequencies are placed on the ground wires the noise levels over which they must work are very much lower. This should permit the use of power levels on the ground-wire pair about equal to the level of the harmonics normally present on the phase wires. Also, it would be more practical to transpose this ground-wire pair than would be the case with the phase wires. Thus the possibility of satisfactory coordination between supervisory control circuits and telephone lines looks very much more hopeful, when the ground wires are so employed.

W. I. Woodcock: We have encountered conditions similar to those mentioned by Mr. Boddie in connection with his Fig. 4, which shows a 4-mi. spur. In our case a tap line was run to Decatur from the line between Sheffield and Huntsville. Calculations show that this tap has about the same resistance as the line of Fig. 4. When this tap line was constructed communication on the main line was made impossible until the carrier frequency was changed.

C. E. Stewart: (communicated after adjournment) Messrs. Robinson and Woodcock refer to two systems of supervisory control. Attention is invited to a third method which consists of using high-frequency carrier-current impulses operating over the insulated overhead channel. This method eliminates the necessity for expensive coupling which is required if the impulses are transmitted over the power conductors. A supervisory equipment of this kind has been in successful operation since October

1926, on the Chicago, South Shore and South Bend Railroad System.[2]

C. A. Boddie: Mr. Boeck seems to think that simplicity and reliability do not go together. My experience, which applies to quite a variety of equipment, is that simplicity almost inevitably leads to reliability, and that complexity tends toward lack of reliability. That is the answer I would give to the system which he proposes, whereby a single frequency is used for communication. Any single-frequency system is inherently less stable than a corresponding double-frequency system. The particular system advocated suffers from the additional complications arising from the suppression of one sideband and the fundamental.

We must bear in mind that the communication which we are attempting to obtain is of vital importance. Stability and reliability are first and we should select for this service only those means which are unquestionable.

I would call attention to a feature which Mr. Woodcock and Mr. Robinson have stressed several times in their paper, namely the matter of maintenance. A commercial telephone system has a corps of men who are thoroughly conversant with all the details of their equipment. Under such conditions complicated equipment can be successfully operated, yet this same equipment will fail under the operating conditions met with on a power system. In view of the operating conditions on a power system I think that the equipment which Mr. Boeck advocates is fundamentally a move in the wrong direction.

I was much interested in Mr. Boeck's remarks on the operation of his new system on a line out West. The line he refers to is the Pacific Gas and Electric 220-kv. line. He made the statement that it was utterly impossible to meet the conditions on these lines with standard apparatus. I wish to oppose that view as I was on that particular project myself. I talked over that line with standard apparatus and wish to say that the quality of the talk delivered was of such a high order as to leave little to be desired. The equipment we used was of the same type as that which Mr. Woodcock has been using so successfully in Alabama, and which is in successful operation in many other parts of the country. It is of simple design in which doubtful elements have been carefully excluded. It provides true duplex operation by utilizing two frequencies. The known fluctuations in power-system conditions are met by providing 250 watts of communication energy.

It is true, as Mr. Boeck says, that the standard equipment furnished by his company demonstrated its "utter inability to meet the conditions imposed by this particular network." That statement is not general as applying to all equipment, but only to a particular design.

The power company in this case had already convinced itself that there was something about a 220-kv. line which made impossible its use as a communication circuit. They thought that the large corona losses were the chief obstacle. Imagining the line to be unusual they felt that the design of equipment which would work on this line must also be unusual, and very naturally accepted the design advocated by Mr. Boeck.

Mr. Anderson points out the difficulties he has had due to interference between two types of equipment operating on his system. These two types of equipment are in general similar except that one is designed to develop 250 watts of communication energy, whereas the other equipments develop only 1 watt normally. The interference arising between these two classes of equipment is due to some extent to the great difference in power level. The low-power equipment is particularly susceptible to interference due to the type of receiving circuit used. Discussions are going forward under the direction of the N. E. L. A. looking toward the elimination of interference between equipments of different manufacture. It might be said in general that most of the low-power equipments which have been manufactured to date are very susceptible to interference, as a result of the broad tuning properties of the receiving circuits which have been used. The circuits in the high-power equipment have been very greatly improved for the purpose of rendering these equipments less susceptible to interference, and to improve the quality of modulation. The manufacturers of the low-power equipment have already expressed a willingness to make improvements in their circuits when interference arises.

There are serious obstacles to go to such high frequencies as 200,000 as suggested by Mr. McCurdy. At these frequencies very short spurs of ¼ to ½ mi. offer serious obstacles. So many of these are encountered on any commercial power system as to render this band of frequencies practically unusable. Our experience is that the best operating region is in the vicinity of 50,000 cycles, and that the desirable range extends as low as 25,000 and as high as 100,000.

Mr. Boeck asked about Fig. 12 of our paper. The chokes for stabilizing the particular section of line have been installed, but no curves have been run to show just what improvements have been made. The installation of the chokes has resulted in a very noticeable improvement in the quality of modulation.

I neglected to point out the efforts we have made to avoid tuning to too narrow a band of frequencies. As shown in Figs. 17 and 18 we have a flat-top curve. This was obtained by the use of the coupled circuit shown in Fig. 16. Its sole purpose is to broaden the frequency band so as to prevent distortion of speech. Mr. Boeck feels that the installation of resonant choke coils will interfere with the free use of other channels on the line. These chokes, in general, act only at the particular frequencies for which they are designed, and have little or no effect on other frequencies. The installation of chokes will not appreciably interfere with the free use of a line for other channels. Here in the South there will soon be in operation four simultaneous two-frequency communication channels.

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[2] See *Carrier-Current Selector Supervisory Equipment*, Stewart and Whitney, A. I. E. E. Trans., Vol. XLVI, 1927, p. 431.

Impulse Flashover of Insulators

BY J. J. TOROK* and W. RAMBERG*
Associate, A. I. E. E. Non-member

Synopsis.—For the most part this paper is a discussion of the mechanism of insulator flashover. The breakdown of air between electrodes, with particular consideration of the effect of various factors upon the flashover characteristics of insulator strings equipped with arcing rings, is discussed. It is shown that critical dimensions and spacings of arcing rings exist for a given insulator string. If the arcing rings are designed to lie on the safe side of this critical point, cascading flashovers will not occur. If the arcing ring dimensions are below the critical values, cascading may or may not occur depending upon the nature of the applied voltage wave. Data from tests, which determined the limiting physical dimensions of arcing rings that will prevent cascading under all types of impressed voltages, are presented.

* * * * *

INTRODUCTION

TRANSIENT voltages on transmission lines commonly are attributed to three sources: switching, induction from cloud fields, and direct lightning strokes. The most troublesome surges are the last two classes.[1] These surge potentials often exceed the insulation value of the line and a flashover follows. The surge flashover forms an ionized path which is highly conducting, and a short circuit on the energized transmission line results. The subsequent interruption may last for only a few seconds. But, if the power short circuit current shatters an insulator, the line may be out of service for several hours, an occurrence which it is extremely desirable to avoid. Because the power current will naturally follow the path established by the surge, a thorough study of the nature of surge flashover is involved directly in the problem of preventing insulator shattering.

WAVE SHAPES AND SPECIFICATIONS

First, however, some attention will be given to the specification and classification of impulse voltages. The waves produced by prevailing types of lightning or surge generators can be analyzed when divided into two parts, the front of the wave in which the voltage rises from zero to the crest value, and the back or tail which is the part beyond the crest.

A wave often is defined by merely giving the constants of the circuit and the time to reach crest value. This is improper for three reasons: 1, The calculated wave form may be incorrect because of the variable resistance of the sparks closing the circuit; 2, Leads and test apparatus may cause distortion; 3, The crest value is not stated. It is particularly essential that the crest value be given in the above form of specification, since two similar waves having different crest values will have fronts of different steepnesses although they may reach their respective crests in the same total time. Because of the lack of a standard specification, where flashover tests are involved the authors have been defining the wave front in terms of the average rate of voltage rise of the "active portion," in kilovolts per microsecond. By "active portion" is meant the part of the wave between the 60-cycle crest flashover voltage and the surge flashover voltage for the particular wave considered. This is illustrated in Fig. 1. Assume that an insulator has a 60-cycle crest flashover voltage corresponding to point A on the wave and that flashover occurs at point B when this particular wave is impressed. No surge with a crest value below A will cause a flashover. Also, the part beyond B has little effect since the breakdown has already occurred. Therefore, the section $A\,B$ has been designated the active portion. Symbolically the rate of rise is $(E_B - E_A)/(t_B - t_A)$ where E and t represent voltage and time respectively. The impulse ratio has been defined as the ratio E_B/E_A, but it should be remembered that this term is meaningless in itself. It must always be accompanied by the characteristics of the wave to which it corresponds. Only waves in which the active portion is on the front of the wave will be considered in this paper. When this is the case, a chopped wave is obtained and the effect of the tail of the wave is eliminated.

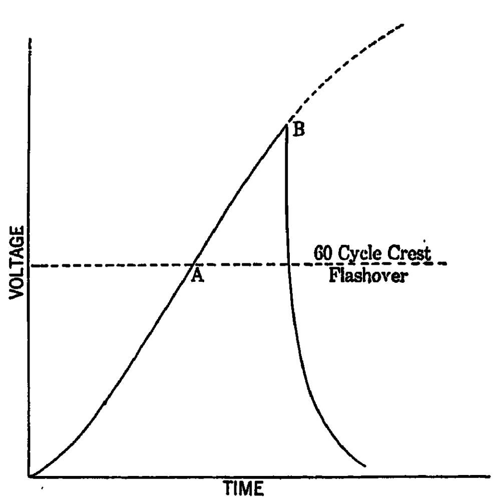

FIG. 1—ILLUSTRATING THE ACTIVE PORTION OF AN IMPULSE FLASHOVER VOLTAGE WAVE

After trying and discarding most of the known systems for the determination of wave front, a new method was developed. The generator voltage is reduced by means of a resistance potentiometer, and the low-voltage wave is impressed upon a transmission line. Here, the wave is chopped with a sphere gap, resulting in a wave of the general form shown in Fig. 1. The chopped wave travels along the line and is impressed on a resistance capacitance circuit. From measurements of the chopped wave voltage and of the condenser voltage, the wave form can be calculated. This is a step by step method and necessarily long and tedious. Hundreds of voltage applications must be made for the determination of a given wave, and the method is valid only for the front of the wave. Check tests with the cathode ray oscillograph prove its correctness.

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*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

[1] For numbered references see Bibliography.

Presented at the Regional Meeting of the Southern District of the A. I. E. E., Atlanta, Ga., Oct. 29-31, 1928.

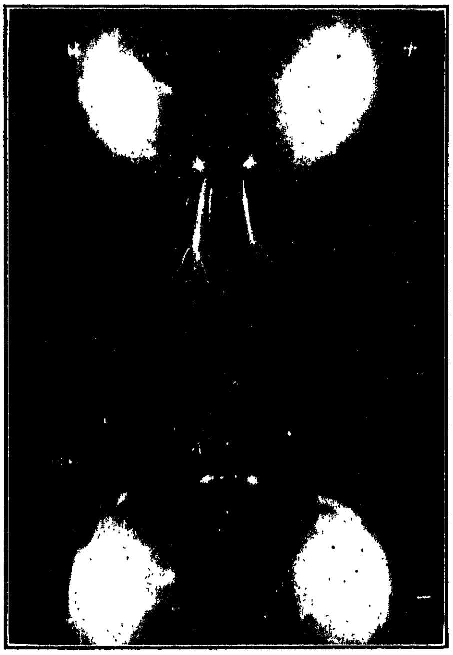

FIG. 2—STREAMER FORMATION PRECEDING BREAKDOWN OF AN AIR-GAP

PRELIMINARY TESTS

One of the first effects noticed was that the nature of the flashover of a string of insulators changed quite perceptibly with different types of applied voltage waves. When the active portion was at the crest of a wave or even on the front of a slowly rising wave the arc sometimes cleared all or nearly all the insulators. But, when breakdown occurred on the front of a steep wave, the arc formed between the metal parts of the insulators, cascading the string. Even with many forms of arcing rings and horns, cascading resulted when steep waves were applied. In designing arcing rings for an insulator string, the first consideration is to ensure that all arcs will take place between the rings. At the same time it is desirable to maintain or increase the flashover voltage of the string by improving the gradient along the string. However, the flashover voltage between rings under all conditions must be less than that of the string with improved gradient. Obviously, from the above, the most difficult condition to satisfy is the prevention of cascading with rapidly rising voltages, and this really includes all others.

We can now summarize the factors involved in a study of the surge flashover of insulators, as follows: the characteristics of the applied voltage, the breakdown of air at atmospheric pressure, the electrostatic field or voltage stress distribution, and hence, the nature of the electrodes.

BREAKDOWN OF AIR

Laboratory experiments have furnished considerable information on this subject. The suppressed discharge,[2] in which the voltage is reduced suddenly to zero before breakdown is completed, shows very clearly the ionization processes. The air is left in an ionized condition, and the light emitted by recombination or by its secondary effects in the ionized sections can be seen or recorded photographically.

The photographs show the effect of extensive ionization especially at the most highly stressed points. Here, the stage of thermal ionization[3] is reached, and small white streamers are found growing from the electrodes as in Fig. 2. Since these streamers already have the properties of arcs,[3] they can be regarded as needle electrodes extending into the field. Therefore, the gradient at their tips will be very high, resulting in rapid growth.[3] As the streamers grow, the effective gap length is reduced and their development is accelerated. This process continues until the entire gap is spanned by the streamers. When this stage is reached, the gap is said to be broken down.

Thus, it is seen that the breakdown of air is a progressive process, and it requires a finite time or progresses at a finite speed. The speed of formation of the streamers depends upon the field through which they progress. Preliminary time lag tests with various types of fields have shown that the speed of formation is a function of the field distribution. The more homogeneous the field, the faster the streamers will develop, since, under these conditions, higher gradients at the tips of the streamers are possible. For instance, the streamers grow much faster in the uniform field of a sphere gap than in the non-homogeneous field of a needle gap. Since a definite time is required for the streamers to grow, in the breakdown of any gap, there is a definite time lag. A typical breakdown curve is shown in Fig. 3. The faster the applied voltage rises, the higher is the value that it will reach before breakdown occurs; and for the slower rates of rise, the breakdown voltage approaches the 60-cycle or static value. The nature of the time lag curve of an air gap depends upon the uniformity of the electrostatic field, and, therefore, upon the gap electrodes.

BREAKDOWN OF INSULATORS

The flashover of a string of insulators is not as simple a process as the breakdown of air between electrodes. A knowledge of the electrostatic field and of the stress distribution along the string is necessary. Calculations based upon the potential theory advanced by Ollendorf[4] have been made and checked in the laboratory. Ollendorf replaces the insulator string by two spheres of suitable diameter, one representing the line insulator, and the other the ground insulator. He neglects the effect of the intermediate insulators upon the field by considering that their charges are bound. Thus, the effect of any charge is nearly neutralized by an equal and opposite charge displaced no more than the length of an insulator. Below breakdown values, voltage distribution curves calculated with these assumptions check closely with experimental curves. Fig. 4 shows the distribution on a plain string of seven suspension insulators raised to breakdown potential. Most of the stress is across the two units adjacent to the line. The seventh or line unit is stressed well above its breakdown value. However, there is a current between the porcelain sections of the string tending to equalize the stresses across the units. This is a conduction current through the air, and the maximum possible current density without thermal ionization is low. Since time is required to transfer the charge, the average rate of voltage rise determines the equalization effect of this current. Therefore, with a rapidly applied voltage, one insulator will reach its breakdown value before the other units of the string. Streamers will start to form around this highly stressed unit. When it is shunted by streamers, its potential will be thrown across the remaining units causing a new voltage distribution. The process continues at an increasing rate until the breakdown is completed. A time lag or breakdown curve similar to that of an air gap exists for the flashover of an insulator string.

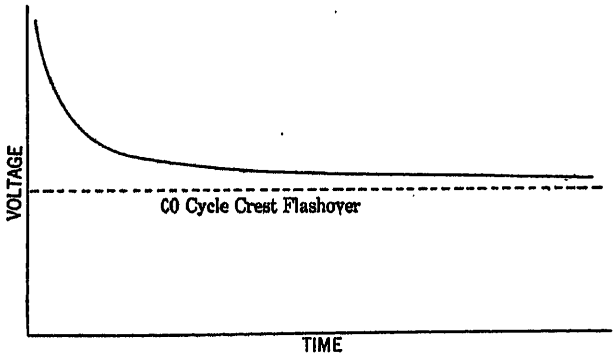

Fig. 3—Typical Breakdown Curve of an Air-Gap

Arcing Rings

We may now consider a typical insulator string equipped with arcing rings. Data on a seven unit string equipped with 19-in. diameter rings of ¼-in. diameter material are available. The rings were located 3.8 in. from either end of the 39-in. string. Surges with a rate of rise greater than a certain critical value invariably cascaded the string. Surges with lower rates of rise struck between the rings. The comparative breakdown curves may be constructed as in Fig. 5. Since the rings have a lower 60-cycle breakdown value, the active portion of a given wave is reached at a lower voltage for the rings than for the insulators. The curves must cross at a point corresponding to the critical rate of rise. It will be noticed that, for slowly rising waves, the active portion for the insulators may not be reached.

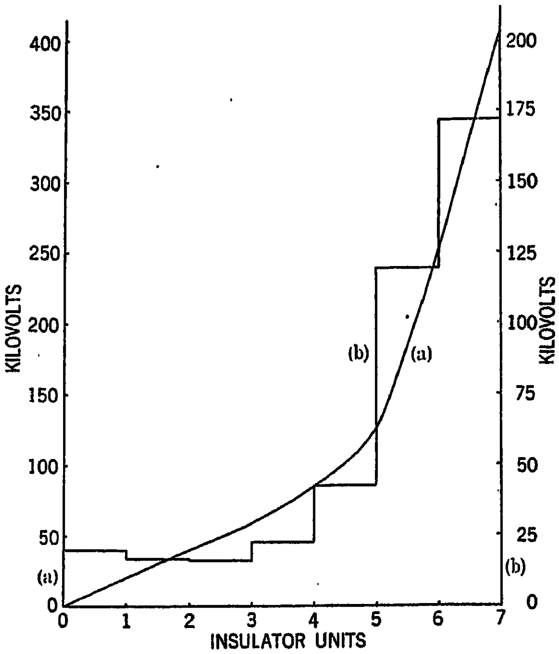

Fig. 4—Voltage Distribution (*a*) and Voltage per Unit (*b*) on a String of Seven Insulators

The following physical explanation may be made.

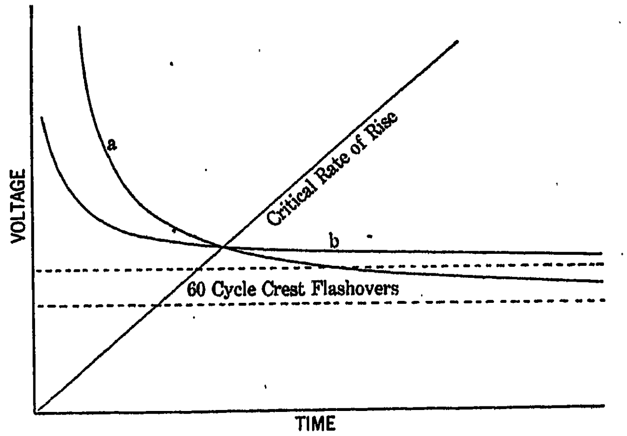

Fig. 5—Comparative Breakdown Curves for an Insulator String (*b*), and for an Air-Gap Between Arcing Rings (*a*)

For slow rates of voltage rise, the streamers forming from the rings span the entire gap before the active portion for the insulators has been reached. For moderate rates of voltage rise, the potential on the insulators reaches the active or streamer forming portion of the wave, but not until the ring streamers have almost completely spanned the gap. For rapidly rising voltages, the ring streamer development is sufficiently slow to permit the insulator potential to rise above breakdown value. Hence, the insulator streamers develop into a cascading breakdown.

The rapidity of the insulator streamer development may be explained with the aid of potential distribution curves. For strings equipped with arcing rings, Ollendorf's theory has to be extended. Each ring is replaced by a ring of charges coinciding with the center of the arcing ring. Then, the charge distribution for rings and insulators that will satisfy all mutual effects and maintain the parts at their proper potentials is calculated. Fig. 6 shows the potential distribution for the same arcing ring arrangement as above. The distribution has been improved considerably over that of the plain string (Fig. 4). The most highly stressed unit is now No. 6, the second unit from the line end. Under a high voltage surge, streamers will form across this unit and throw its potential across the remaining units giving a new distribution as in Fig. 7. Units 5 and 7 are now stressed above breakdown value and will flash over simultaneously. Further analysis is impossible because of the changes in charge distribution, but it is probable that the remaining units will break down in pairs. Thus, the effective streamer development around the insulators is accelerated to such an extent that its growth is faster than that of the arcing ring streamers. Fig. 8 is a photograph of this type of breakdown on an eight unit string. The top insulator has already flashed over while units 2 and 4 are in the process of breaking down. The streamer formation from the rings is apparent.

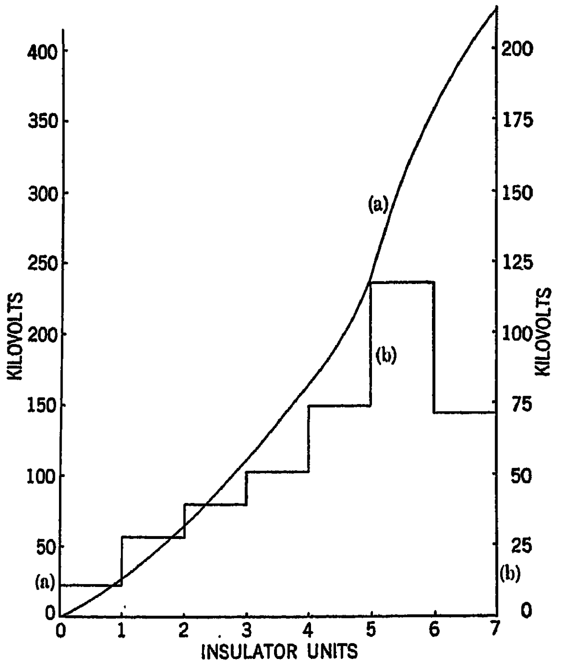

FIG. 6—VOLTAGE DISTRIBUTION (*a*) AND VOLTAGE PER UNIT (*b*) ON A STRING OF SEVEN INSULATORS EQUIPPED WITH ARCING RINGS, AT BREAKDOWN

Since it is possible to calculate the potential at any point around the rings, the gradients can be determined. Calculated gradients along the line between rings and along the units of the string are shown in Fig. 9. In this case the maximum gradients are at the surfaces of the arcing rings. Hence, the streamers will develop from the rings and meet in the middle of the field.

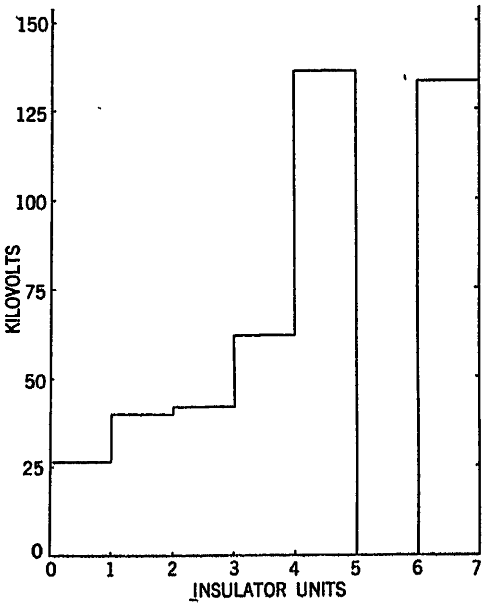

FIG. 7—VOLTAGE PER UNIT ON A STRING OF SEVEN INSULATORS WITH ARCING RINGS

After unit six has flashed over

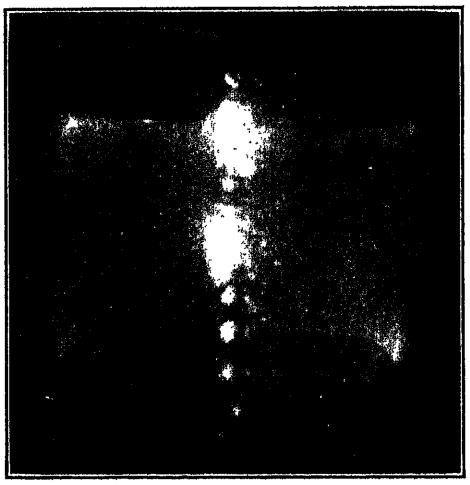

FIG. 8—SUPPRESSED DISCHARGE ILLUSTRATING THE SIMULTANEOUS BREAKDOWN OF TWO UNITS

Another important factor in the problem will now be considered. Assume that a string of insulators equipped with arcing rings as in Fig. 10 is subjected to an impulse voltage above the breakdown value. The metal parts of each insulator in the string will be raised to corresponding potentials, and a definite difference of potential or electric field will exist between each part of the string and each arcing ring and between the arcing rings. The gradient is highest at the ring surface, and ionization will begin and the streamers will start to form at this point. There are two distinct components to the forces on the streamers, a ring-to-ring component and a ring-to-insulator-string component. These cause the streamers to branch out. The action is complicated by a progressive change in the field due to the conductivity of the streamers. However, the relative values of the components determine the rapidity with which the branches develop, and therefore, whether the arc passes directly between the arcing rings or is drawn into the insulator string as shown.

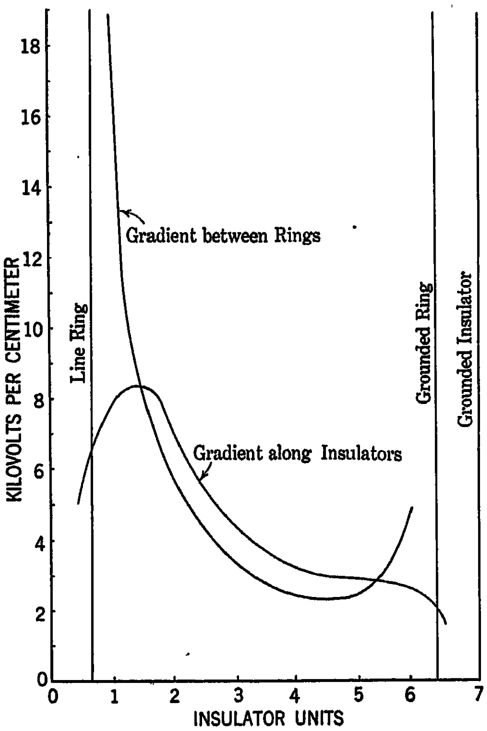

FIG. 9—VOLTAGE GRADIENTS AT BREAKDOWN ON A SEVEN UNIT INSULATOR STRING EQUIPPED WITH ARCING RINGS

Laboratory experiments indicate that the streamers upon formation are fairly high in resistivity, and probably only a part of the charge is transferred to their tips. For this reason, the streamers of opposing electrodes will have less effect upon each other than might be expected. However, as the streamer progresses, the insulator-streamer component increases due to the relatively higher potential of the insulators at this point. This effect is increased further under steep surges by the unbalanced rise of potential on the insulators. A slight bending of the streamer toward the insulators produces an increase in the streamer-insulator component which forces the streamer to develop still further in toward the insulators. Thus, a slight bending or branching of the streamers in the early stages of flashover will result in a cascading or partial cascading flashover. This point is particularly important for long strings such as 220-kv. transmission line insulation.

We may now determine the effect of various physical arrangements of the arcing rings upon their flashover characteristics. It is obvious that a homogeneous field between the rings is desired to speed up the streamer formation. The nearer the surface of the ring approaches that of a sphere, the more uniform the field will be. Therefore, the ring must be made of relatively large diameter material. To prevent the streamers from being drawn into the string, a ring of relatively large radius must be used. To aid in obtaining these results the spacing or distance between the rings can be reduced, and this is usually necessary. However, due to the improvement in voltage distribution along the string resulting from the grading effect, a flashover voltage comparable to that of the plain string can be maintained. Obviously, the grading effect is lessened by an increase in ring radius, and the most desirable arrangement for a particular application will be a compromise.

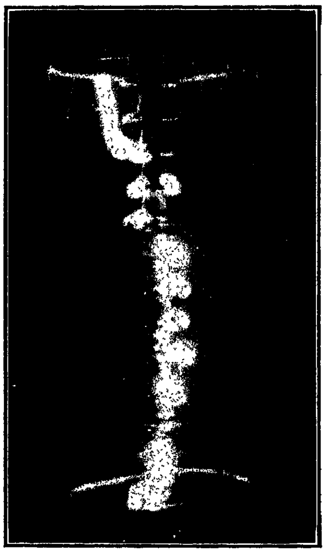

FIG. 10—SURGE FLASHOVER OF AN INSULATOR STRING WITH IMPROPERLY APPLIED ARCING RINGS

ARCING HORNS

The arcing horn has characteristics similar to the needle gap. The stress distribution between opposing horns is very poor, since the section surrounding the horn tips has a relatively high gradient. Through a field of this nature the streamers will develop slowly, and the potential across individual units will have time to build up and cause cascading. To overcome this sluggishness of operation, the distance between the tips must be reduced considerably. This adjustment is doubly effective; the point at which breakdown begins or streamers start to form is lowered, and the breakdown distance is reduced. However, decreasing the spacing has the serious disadvantage that the insulation of the line is lowered. When an arc exists, it must terminate at the horn tips and is quite likely to be blown into the insulators.

The characteristics of the arcing ring are inherently much better. The stress distribution is uniform permitting the streamers to grow rapidly. Consequently, spacings which do not lower the line insulation can be maintained. When an arc occurs between rings, it can travel around the rings. Hence, there is little chance of the arc being blown into the insulator string.

TESTS

Test data on various arcing ring arrangements have been accumulated. Standard suspension insulator units 10 in. in diameter by 5⅝ in. spacing were used in the tests. Rings of ¼ in. diameter copper were first used to facilitate variation of the ring diameter and ring to ring spacing. The average rate of rise of the active portion of the generated wave was 7000 kv. per microsecond. This is somewhat steeper than lightning produces on transmission lines, as indicated by available data.[1] However, extensive measurements of voltage or wave form were not made.

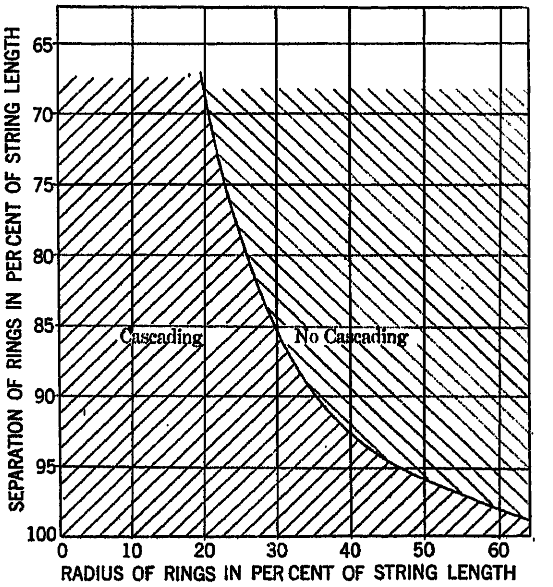

FIG. 11—CRITICAL ARCING RING ARRANGEMENTS FOR CASCADING AND NON-CASCADING FLASHOVERS ON A SEVEN UNIT (39 IN.) INSULATOR STRING

First, the rings were set at a definite spacing, that is, a definite percentage of the string length. The radius of the rings was increased until cascading ceased entirely with repeated voltage application. Thus, the minimum ring radius for a given spacing was obtained. Similarly, the maximum spacing for a given ring radius was determined. Fig. 11 where critical ring spacings and ring radii are plotted in terms of the string length, shows graphically the results of such a test for a seven unit string. The curve divides the cascading and non-cascading regions. Thus, in order to keep the ring spacing or flashover distance above 90 per cent of the length of the plain string, for this particular case, the ring radius must be 40 per cent of the length of the string. Where the ring radius is limited by tower clearances, the curve gives at once the maximum ring spacing. Similar tests were made with ring material of 1½-in. and 2-in. diameter. The results for the seven unit string are shown in Fig. 12. For close spacings the larger diameter material is of no advantage. At greater separations the larger diameter material permits the use of rings of smaller radius.

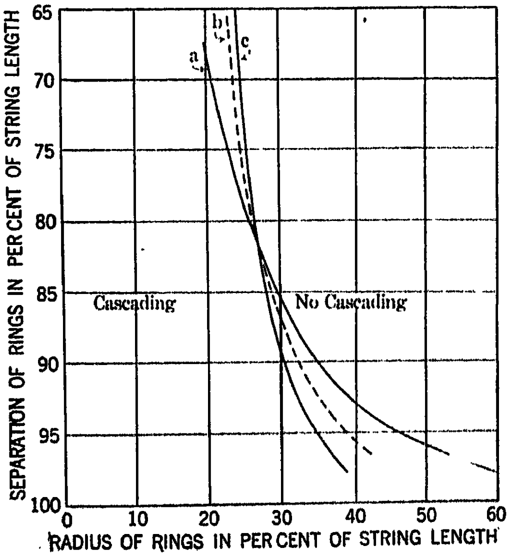

FIG. 12—CRITICAL ARCING RING ARRANGEMENTS; (a) ¼-IN. DIAMETER MATERIAL, (b) 1½-IN. DIAMETER MATERIAL, (c) 2-IN. DIAMETER MATERIAL; FOR SAME STRING AS FIG. 11

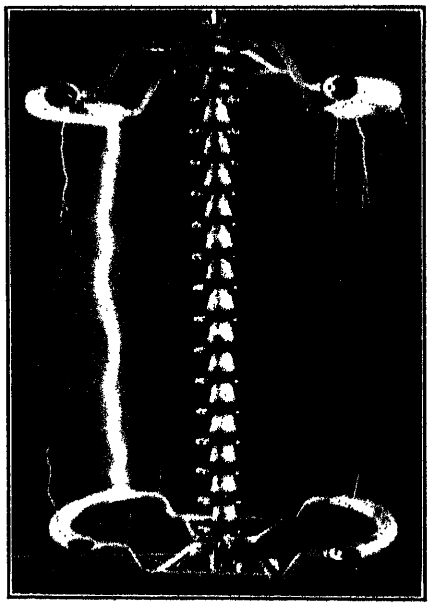

FIG. 13—ARCING RINGS DESIGNED FOR A 16-UNIT INSULATOR STRING

With this information arcing rings for any particular set of conditions can be designed, as illustrated by the following example. Assume a line with seven suspension units 38.5 in. in length and with tower clearances which limit an arcing ring to a radius of 14.5 in. The ring radius is thus 38 per cent of the string length. For two inch diameter material, Fig. 12 indicates that the maximum spacing for this ring radius is 96 per cent of the string length. To secure a slight margin of safety by avoiding the critical cascading point, a spacing of 90 per cent might be chosen. Thus, the most satisfactory arcing rings for these conditions have the following dimensions:

Material diameter	2 in.
Ring diameter	29 in.
Ring spacing	35 in.

In some cases, clearances will not permit a ring of suitable diameter, and an oval or elliptical ring must be used. For this type of ring, the sections at the ends of the major axis must be made the active or working parts. This is accomplished by making the spacing between the active parts less than between the sections around the minor axis. Fig. 13 shows oval rings designed for a 16 unit string. The arc striking sections are of large diameter pipe and furnish the minimum breakdown distance for the string. Care must be taken to avoid abrupt bends in changing from one section of the ring to another. Fig. 14 shows the streamer formation at the stage close to complete breakdown on the same rings.

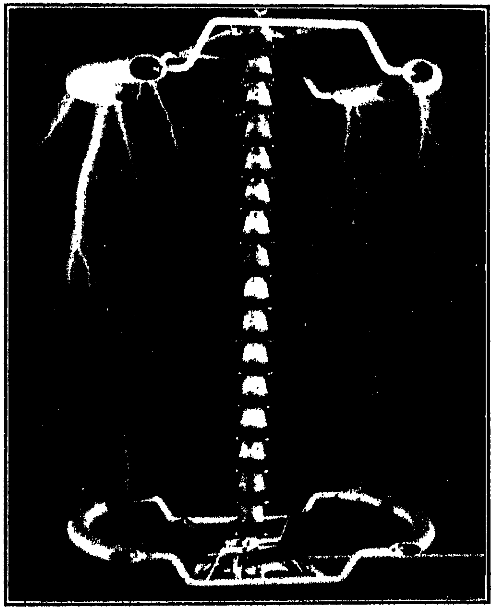

Fig. 14—Streamer Formation During Breakdown

Conclusions

1. The breakdown of air is a progressive process requiring a finite period of time for the streamers developing from one or both electrodes to span the distance between electrodes. The time required is a function of the average gradient of the field.

2. The flashover of a string of insulators is a similar though more complicated process.

3. The nature of the flashover depends upon the rate of rise of the applied voltage. Cascading of the units of an insulator string is more likely to occur the faster the rate of voltage rise.

4. Cascading flashovers occur on the application of rapidly rising voltages because of the limited values of the leakage and conduction currents which tend to equalize the stress distribution of the units of the insulator string.

5. The path formed by the surge flashover furnishes a low resistance path for the power follow current.

6. Arcing rings will prevent cascading flashovers provided the time lag characteristic curve for breakdown between the rings is below the corresponding curve for flashover of the insulator string. This condition may be satisfied by conforming to definite physical relations between the ring to ring spacing, the radius of the rings, and the diameter of the ring material, as functions of the length of the insulator string to be protected. Furthermore, the radius of the arcing rings must be great enough to prevent the streamers from being drawn into the insulator string after they have started to form at the active sections of the arcing rings.

7. Arcing horns are unsuitable because of their high time lag characteristic, the decrease in flashover voltage necessary, and the likelihood of the arc being blown into the insulator string.

The authors wish to express their appreciation of the assistance contributed by Messrs. J. Slepian, C. L. Fortescue, and P. H. McAuley.

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Discussion

For discussion of this paper see page 254.

A Study of High-Voltage Flashovers

BY JOSEPH T. LUSIGNAN, Jr.[1]

Associate, A. I. E. E.

***Synopsis.**—A brief discussion is given of the various forms of electrical discharges as they are characterized by the physicists.*

Oscillographic records secured of voltages and currents, both before and during the flashovers, are reproduced and discussed. Polarity tests are described in which the electrode shape and spacing were found to determine the sign of the half-cycle at which flashovers would start.

Photographic results obtained with moving films are illustrated, showing the various stages of a flashover from the formation of the corona discharges, through the initial sparkover, to the development of the half-cycle arc channels. The flashovers studied ranged from several feet to 22 ft. in length.

Spectrographic analyses of the different stages of a flashover are described, wherein it is possible to gain some knowledge of several of the factors contributing to the conductivities of the various stages. Several of the spectra obtained are illustrated along with a comparison spectrum of lightning.

With the knowledge gained from the laboratory studies made, the probable history of a high-voltage a-c. flashover is summarized.

* * * * *

INTRODUCTION

The object of the study described here was to secure a better understanding of the development of a high-voltage a-c. flashover, particularly with a view to investigating the successive stages of discharge involved, and the various factors contributing to their existence,—from the initial localized breakdown of air, or corona, to the final stage of a fully developed power arc. The entire experimental work was carried out in the Harris J. Ryan High-Voltage Laboratory at Stanford University. Due to the limited kilovolt-ampere capacity of the laboratory equipment and of the connected power line supplying it with energy, it was not possible to secure arcs of sufficiently high-current density and of adequate time duration to simulate a truly high-power arc as might develop on a transmission system. However, from the analyses that it was possible to make of the arcs formed, it is felt that a sufficient knowledge was gained of the various factors that would enter into the later stages of a power arc, to make possible the completion of the story, and in that way allow of the securing of the entire history of a high-voltage flashover.

ELECTRICAL DISCHARGES IN GENERAL

Our knowledge of the mechanism of electrical breakdowns is largely derived from the work of the physicists who, as a rule, have used short gaps with simple forms of electrodes and gases in order to bring in as few contributing factors at a time as possible. Although the particular problem here involved the study of 60-cycle discharges through comparatively long distances and under atmospheric conditions, it was nevertheless essential to turn to the findings of the physicists in order to secure better analyses of the results obtained.

Dr. K. T. Compton recently gave a valuable paper before the Institute[2] in which he described the nature of the electric arc and other related phenomena. He particularly shows the difficulty of always drawing sharp lines of differentiation between arcs, sparks, glow discharges, and coronas, due to the fact that they share so many characteristics. In counter-distinction to the spark, the arc is usually considered to involve the greater current density with a lower voltage drop, yet there are sparks obtained which carry more current with less voltage than some arcs. As a rule, physicists differentiate the two by means of the respective cathode voltage drops, the spark having considerably the greater of the two, while some add the condition that the arc must have a negative volt-ampere characteristic.

The engineer is used to defining the arc in various ways, but generally he associates it with types of conduction occurring when metal vapors from the electrodes furnish the conducting path, coupled with possible thermionic emission from the cathode, electrons being emitted in the same manner as from the hot filament of a vacuum tube. Physicists, though, have obtained arcs between rare earth oxides in air which are maintained solely by thermionic emission. There are still other continuous discharges drawing fairly heavy currents and with current characteristics of arcs, which exist in gases between non-volatile electrodes and without hot cathodes. These, therefore, involve neither metal vapors nor thermionic emission. The ordinary neon discharge tube has characteristics[3] which would probably allow it to be cited in this category.

The spectroscopist has characterized arcs and sparks in terms of the spectra produced. In general he would define an arc as any discharge leading to the excitation of lines or bands in the spectrum, indicating excited states of neutral atoms or molecules, or possibly the first stage of ionization. Sparks would be characterized as discharges leading mainly to spectral lines indicating higher stages of excitation and ionization. The difference depends mainly on the drops of potentials through which the colliding electrons, causing the radiations, have fallen.

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[1] General Electric Company, Pittsfield, Mass., formerly Fellow in Electrical Engineering, Stanford University.

[2] See bibliography for references.

Presented at the Regional Meeting of the Southern District of the A. I. E. E., Atlanta, Ga., Oct. 29-31, 1928.

OSCILLOGRAPHIC STUDY OF FLASHOVERS

Voltage and Current Waves. In this study, voltage records of flashovers were first secured by attaching a shielded water column resistance to one of the high-voltage electrodes and inserting an oscillograph element into the ground end of the column, so as to obtain current waves there, which would be indicative of the electrode voltages to ground. Two of the records obtained in this manner are shown in Figs. 1 and 2.

Fig. 1 shows the voltage wave of the initial part of a 20-ft. flashover, the formation point of the arc being on the half cycle where the sharp drop in voltage occurs. Each half cycle after that is seen to start with a brief rise in voltage which breaks down the gap again and allows the arc to re-form, whereupon the voltage drops for the remainder of the half-cycle. If the potential applied to the electrodes is allowed to decrease after the arc forms, then the latter may break of its own accord. Fig. 2 shows the corresponding voltage wave of the final stage of such an arc. The record represents two revolutions of the film, and starts at *a* on the irregular wave of the arc itself. Here it is again apparent how each half cycle starts with a brief rise in voltage which each time breaks down the gap, but as the record progresses and the current decreases due to the applied voltage being allowed to fall, the voltage has an increasingly harder task to maintain the half cycle discharges so that the initial half-cycle voltage needles continue to increase in magnitude. Finally at the point *b* the voltage is no longer able to re-form the arc for that half cycle and the regular open-circuit voltage wave starts, which continues around on the film a second time and drops to zero at *c* when the circuit breaker opens.

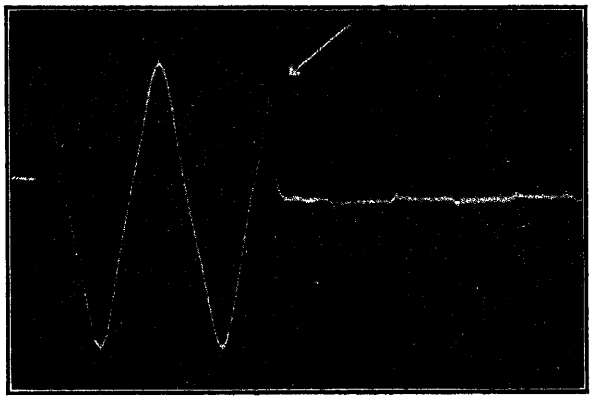

FIG. 1—VOLTAGE WAVE AT START OF 60-CYCLE FLASHOVER

Arrow indicates point of breakdown

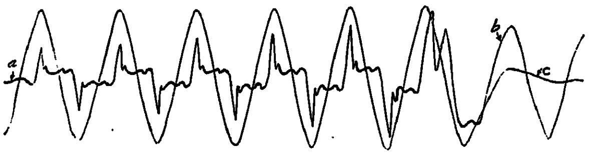

FIG. 2—VOLTAGE WAVE AT END OF 60-CYCLE FLASHOVER

Arc broke due to lowering of applied voltage

In order to secure simultaneous current and voltage records prior to flashover, a two-element oscillograph was mounted at the top of the water column. One element was connected into the water column circuit so as to obtain a wave indicative of the electrode voltage, while the other element was connected to an insulated lead running to the point of the electrode, thereby allowing a wave of the discharge current from the point only to be secured. One of the records obtained in this manner is shown in Fig. 3. The current wave is seen to be decidedly unsymmetrical with respect to the two halves of each cycle, indicating the rectifying effect that is always associated with a point in corona. On the positive current crests a series of discharge needles can be detected whereas on each of the negative crests usually but one appears. Current waves, taken as the voltage across the 20-ft. gap is slowly increased from pre-corona values, show that the positive current needles appear soon after corona starts and occur regularly on the positive half cycles. The negative half cycles of current increase in magnitude as the voltage rises, but the brief discharge needles do not appear until almost the point of flashover, when they usually occur but once on a crest. This feature will be seen later to check well with photographic observations taken on moving films.

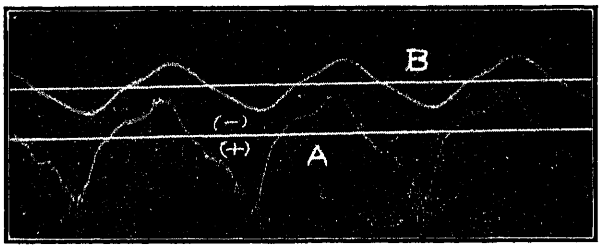

FIG. 3—CORONA CURRENT PRIOR TO FLASHOVER

A. Corona current wave prior to flashover of 20-ft. point-gap
B. Corresponding voltage wave

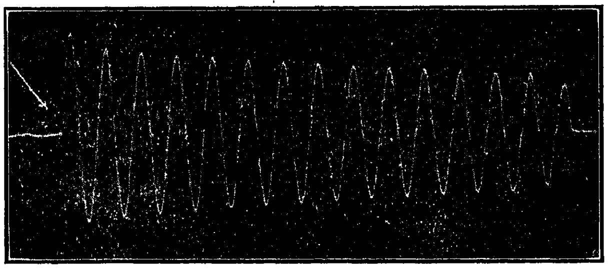

FIG. 4—FLASHOVER CURRENT FROM POINT ELECTRODE OF 20-FT. GAP

Arrow indicates start of flashover of 14½ cycles duration

By using a calibrated shunt on the oscillograph element it was possible to secure a current wave of the flashover itself, the shunt, of course, diminishing the corona current values to negligible magnitudes. Fig. 4

shows an oscillogram taken in this manner. The approximate effective value of the first half cycle of flashover is 1.63 amperes.

Determination of Flashover Polarities. As an added step in the study of flashover characteristics, tests were made to investigate the polarities at which different gaps would arc-over to ground at 60 cycles, and in that way ascertain whether this phase of a flashover took place in any orderly manner. With direct current, the point-to-plane set-up has always been found to arc-over at a lower potential when the point was positive than when it was negative, except at small spacings of the order of a fraction of an inch;[4] therefore, this arrangement was tried first to see whether the same was true for alternating voltages. About 50 flashovers were taken with spacings ranging from 5 to 10 ft., and oscillographic records of the current in each case were secured in the ground end of the high-voltage winding. In every instance the flashover started on the half cycle when the point was positive.

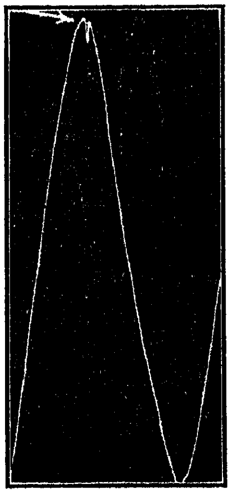

FIG. 5—VOLTAGE WAVE JUST PRIOR TO FLASHOVER OF 18-FT. POINT-GAP

Arrow indicates brief drop in voltage at wave crest due to transient sparkover, one cycle before start of flashover

A similar test was made on 50-cm. spheres with the bottom sphere grounded. With the spheres spaced 50 cm. apart, approximately 50 flashovers were taken, and found to start with the ungrounded sphere negative, which was just opposite from the results with the point-to-plane set-up. The sphere-gap was next opened up to a maximum spacing of 69 cm., and the arc-overs were found to start on both halves of the waves, that is, the spheres flashed over from the upper sphere on either the positive or negative crests. There were about twice as many initial positive flashovers as negative, but an insufficient number was taken (about 40 in all) with which to predict any fixed ratio.

From the above results it seemed that initial local breakdowns due to concentrated field intensities would cause a flashover to start positively from the ungrounded electrode, while, on the other hand, with a more or less uniform field, such as a sphere-gap at close spacing, the arc to ground would form on the negative crest of the wave. To test out this theory roughly, a short ⅜-in. barb was placed on the under surface of the ungrounded sphere, and the gap arced over at a 50-cm. spacing, where it had previously flashed over to ground on the negative crests. However, the barb caused the polarity to reverse and the flashovers started positively. With the same barb on the bottom sphere, the flashovers started on the negative crests, probably because of the lesser field concentration on the grounded sphere. The light from a quartz mercury arc lamp was also played on the spheres to ascertain its possible effect on the polarity of flashovers. It was found to produce no change, but the intensity of the ultra violet light reaching the spheres from the distance away that the lamp had to be mounted was afterwards determined to be very small.

Sixty-cycle polarity tests were also made on shielded and non-shielded suspension insulator strings of 10 and 14 units respectively, where it was found that practically all flashovers to ground started on the conductor positive crests. Occasionally one would take place on a negative crest, but the average was never more than about one out of every 25 discharges. These results would seem to fit in well with d-c. and impulse insulator flashover tests made by Peek[5,6] in which he found the arcs to form on lower positive potentials than negative.

The reasons for the behavior of the various forms of gaps with respect to the polarities of the flashovers can probably be traced to the difference in mobilities of the ions and electrons, and their paths as controlled by the particular electrostatic fields involved.

PHOTOGRAPHIC STUDIES OF FLASHOVERS

For the purpose of securing possible photographic analyses of flashovers, a special camera with a revolving film holder was made. A quartz lens of 2¼-in. diameter, loaned by Mr. Peek, was used in it, and the continuous film placed on the revolving cylinder which was arranged at the focal point of the lens. By driving the cylinder at different speeds it was possible to draw out the discharge figures on the films as much as desired; and by the use of shutters actuated by relays, the films could be exposed to any phase of a flashover.

Figs. 6 to 10 show some of the moving film records obtained in this manner. In each of the figures it is apparent how the path of the first breakdown, shown by the brief but heavy discharge at the start of the first half cycle, practically determines the path of the succeeding half cycles.

The manner in which the streaks of light are drawn out on the film after the last half cycle of arc proved of interest. They undoubtedly can be accounted for in the following manner: The arc itself is probably not more than a fraction of a millimeter in thickness but at the points where it is folded or bent there are several millimeters or more of arc length in the line of vision. Therefore, at these folded points there will be much stronger light intensities which will have greater effects on the photographic film. The ionized gas remains partly incandescent even between half cycles when the current is passing through zero, which densitometer measurements verified, but it is only the more intense folds of the arc that appear to persist on the film between half cycle bands. Accordingly, after the last half cycle, it is these same folds that streak out as if by themselves. Undoubtedly the whole path across the gap remains incandescent, but only those parts that are bent to appreciable length in the line of vision seem to show up on the film, those of the greatest depth lasting longest. In some of the films obtained, these folds persisted as long as three cycles after the arc-overs had ceased, indicating that the gas in the gap remained incandescent that long.

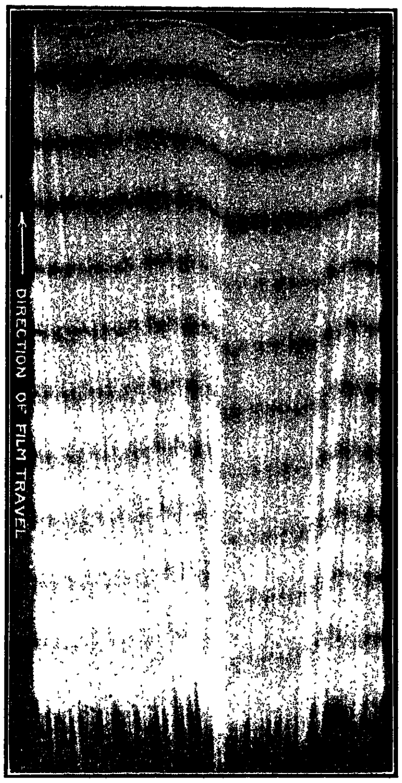

Fig. 6—Reproduction of Moving-Film Photograph of 10-Ft. Horizontal Flashover of 11 Half Cycles Duration Between Pointed Electrodes

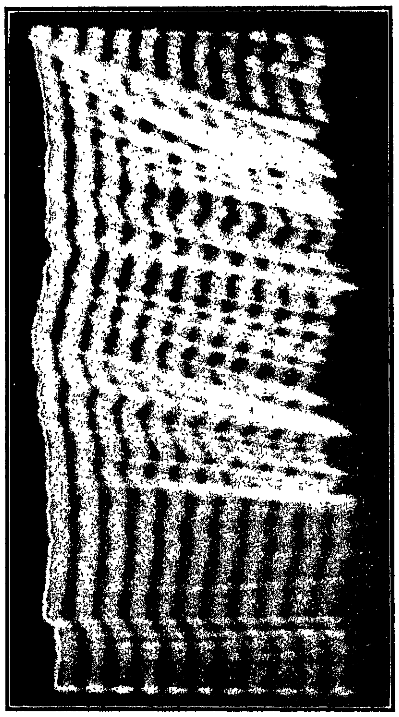

Fig. 7—Nine-Foot Vertical Flashover from Point to Floor

Moving-film photograph of flashover of 11 half cycles duration

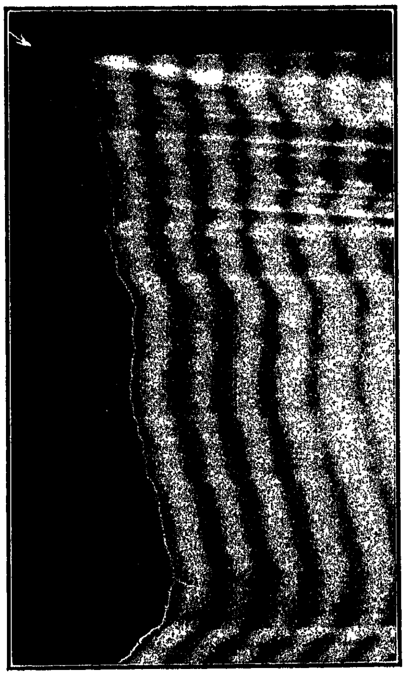

Fig. 8—Start of Nine-Foot Vertical Flashover from Point to Floor

Arrow indicates single intense corona streamer on negative half cycle prior to flashover. Moving-film photograph with film speed approximately twice that of Fig. 7

Fig. 6 is an example of one of the faster moving films wherein the half cycle bands are drawn out to a width of about one inch each. The overload relays opened the circuit in this case in five and a half cycles so that eleven half cycle bands appear on the film. In one test, the generator field was quickly reduced at the start of arc-over so that the arc would break of its own accord after about twelve cycles. The moving film photograph taken in this case showed an appreciable decrease of incandescent gas particles after the last half cycle of arc-over, undoubtedly due to the very low final current density compared to the cases where the opening of the oil breaker terminated the arcs.

In the first work with the 10-ft. horizontal point-gap, both sides insulated, it was noticed that the brush discharges, from each point prior to arc-over, were only perceptible at the positive half cycles on the moving films. When the gap was next opened up to 22 ft., though, discharges appeared on every half cycle just before arc-over. On the films, the alternate half cycles of brush discharge were found to be strikingly similar, while the succeeding half cycles were different, indicating that the positive and negative discharges each had their own decided characteristics. As the point discharge first begins to appear on the moving film with the rising voltage, there can be seen on the negative half cycles, either no visible signs of discharge, or else one heavy stalk or jab with a corona head at the end of it (see Fig. 8), indicating a small voltage drop along its path, so that the field terminates largely at its end and produces a brush head effect there. As the voltage approaches arc-over these intense white negative jabs increase in length and brilliancy, and may occur more than once on an occasional half cycle. The positive discharges, however, seem to be more prolonged over their corresponding voltage crests, branching out continually and to greater lengths than the negative discharges, but with less luminous intensity than the latter. They come in earlier also, and consistently appear at each alternate half cycle. The fact that no long intense negative streamers appeared at the 10-ft. spacing, both electrodes insulated, apparently indicated that they required much higher voltage gradients.

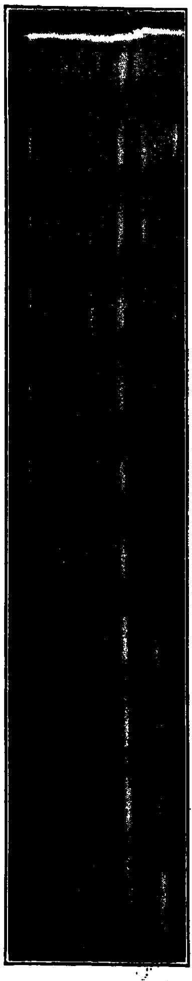

Fig. 9

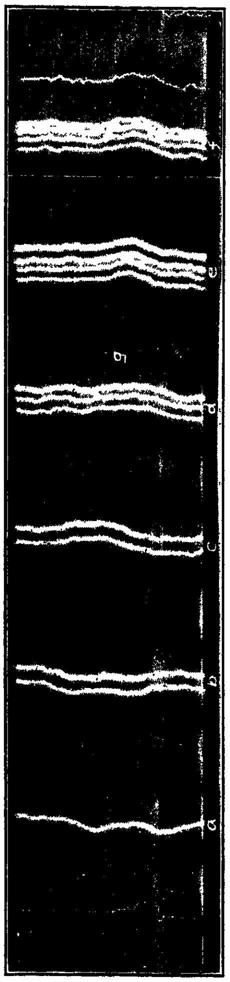

Fig. 10

Fig. 9—Moving-Film Photograph of 60-Cycle Flashover

11 half cycles duration, between 25-cm. spheres, 25 cm. apart

Fig. 10—Moving Film Photograph of 30-In. Discharge from Point to Plane

Air condenser in parallel with gap energized preliminary discharges on five positive half cycles preceding start of flashover

In the work on space charge carried out at Stanford two years ago,[7] it was found that at the start of corona, the region between two conductors was built up to a slight negative potential above ground due to the corona rectification. The sign of the charge soon reversed with increase in voltage and near the flashover voltage the space had been charged up to an appreciable positive potential above ground. Since it is at this point that the long intense streamers appear from the negative electrode, it would seem that they merely serve to dart out at intervals to drain different portions of the field of the heavy positive space charges there.

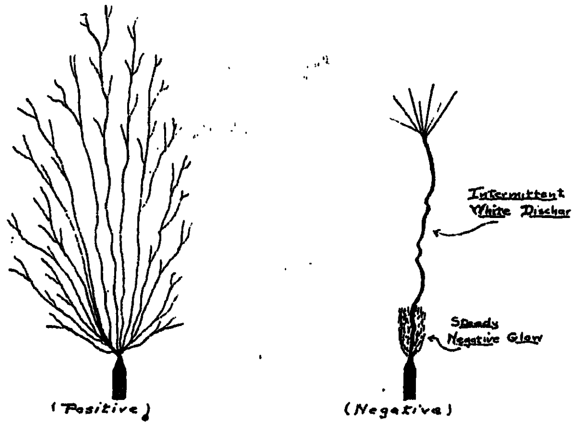

Fig. 11—Corona Point Discharges at One Million Volts

By means of a stroboscope it was possible to check visually the electrode discharge figures obtained on the moving films. At the start of corona the discharges resembled very closely those found by Peek,[8] in that at the negative electrode there was a rather small even glow while the positive electrode exhibited a long dispersing discharge. Both increased in size as the voltage was raised until at a million volts above ground the positive discharge resembled a huge tree-like figure surrounded on all sides by a bluish haze, while at the negative electrode a rather short glow persisted from which intense white streamers, several feet in length, darted out at intervals of a second, more or less. Fig. 11 shows diagrammatically the approximate shape of the positive and negative discharges at a million volts above ground.

The physical appearances of the point brush discharges found above seem to display features which fit in rather well with the oscillographic records of corona current obtained. On these current waves, one of which is shown in Fig. 3, the many needle jabs on each positive half cycle probably serve to supply the tree-like channels continually branching out when the electrode is positive. On the negative current crests the smooth part of the wave is probably indicative of the current supply to the short negative glow, while the single sharp peak with it, if it occurs, would be associated with the ordinarily single heavy streamer that is seen on the negative half cycle on the moving film.

In order to determine the effect of additional condenser capacity in parallel with a discharging electrode, an 8 ft. by 10 ft. mesh plate was supported 4 ft. from the floor and connected to a point 30 in. above the floor. A moving film photograph of the discharge across the latter gap is shown in Fig. 10. The figure represents about one and a half revolutions of the film so that the record overlaps partially. The first visible breakdown occurs at *a* on a positive half cycle. Two discharges each appear on succeeding positive half cycles *b* and *c*. On the next one *d* three occur, and the next *e*, there are four. At the half cycle *f* after four intense discharges have occurred, the arc forms, and persists for the remainder of the record. The arc appears every half cycle and comes around on the film once more, finally ceasing at *g* after 11 half cycles of duration. At the early part of the arc stage, each half cycle is seen to be started by a rather intense breakdown flash. As the arc progresses and the conductivity increases this initial half-cycle flash is found to decrease in intensity.

Since the previous polarity tests showed positive discharges to be particularly favored on point-to-plane set-ups, apparently some of them temporarily bridged the gap above on several positive half cycles before arc-over so that the energy of the paralleling condenser would come in to intensify the brief breakdowns each time. Finally, though, when the voltage had been raised sufficiently, the condenser was able to pour enough energy into the breakdown to render the path sufficiently conducting for an arc to form. From this it would seem that added capacitance might tend to lower the flashover voltage of such a gap a trifle, since it would provide more energy for one of the earlier discharges. Extra resistance for damping or reactance directly behind the point, on the other hand, might have the opposite effect by checking the inflow of condenser energy.

The same test was repeated with 25-cm. spheres, spaced 25 cm. apart, as discharging electrodes, the top sphere being connected to the condenser and the bottom one grounded. There were no visible discharges across the gap on the moving film in this case prior to complete arc-over, as occurred with the point-to-plane arrangement, probably because no appreciable corona brushes appeared from the smooth spheres. The only apparent effect of the condensers was to intensify the initial heavy flash starting the first half cycle of arc-over.

In these last short gap set-ups the initial intense discharges between the electrodes preceding the first half cycle of arc-over appeared to be of highly oscillatory nature on the revolving films. With the longer electrode spacings, particularly those of approximately 20 ft. between points, and of 10 ft. from point to plane, these discharges were extremely brief so that no oscillations could be detected on the moving films. The current oscillograms though usually showed a high-frequency oscillation at the time of initial breakdown, but they were generally of not more than one cycle duration, probably due to the damping effect of the 400,000 ohms of protective resistance connected behind each electrode when attached to the 2,000,000-volt transformer set.

In photographs of laboratory flashovers of insulator strings, condenser-like discharges are sometimes visible along different paths than that over which the actual flashover finally develops. These are undoubtedly initial discharge breakdowns to ground at a time when the voltage was too low to provide sufficient energy ($1/2\ C\ E^2$) to render the path conducting enough for the arc to follow. Fig. 5 shows the oscillogram of a voltage wave several cycles before flashover of a 20-ft. point gap, where a brief drop in voltage at one crest can be seen, which probably occurred simultaneously with some such temporary pre-flashover condenser discharge.

SPECTROGRAPHIC ANALYSIS OF FLASHOVERS

Spectrograms were taken next of the different stages of a flashover in an attempt to identify some of the factors contributing to its various conductivities. By arranging a shutter that would open for only the start of a flashover, it was possible to secure the spectrum of the initial intense discharge which was found to bridge the gap at the beginning of the first half cycle of arc-over on each of the moving film photographs, (of Figs. 6 to 10). Fig. 12A shows one of the spectra, obtained in this manner, of a 10-ft. discharge from a point to a plane. This was identified as the spark spectrum of air and is practically identical with that of lightning, as can be seen from a comparison with a lightning spectrum as obtained by Fox[9], which appears in Fig. 12B. Due to the different dispersions of the two spectrographs used, the separations of the spectral lines are of course not the same, but their order matches up perfectly. In every laboratory flashover so analyzed the initial discharge was found to give the spark spectrum of air. These spark lines were always found perceptibly stronger at the center of the gap than at the electrodes, probably due to the intense breakdown discharge at that point between the space charges built up at the head of the advancing corona streamers from opposite electrodes.

In these spectrograms of the initial spark it was noticed that arc lines of metal vapor appeared at the electrodes. In the discharge of Fig. 12A, where an aluminum electrode was used, typical aluminum arc lines are visible at the left end. In order to ascertain how soon metal vapor appeared in a flashover, a moving film spectrogram of about one inch of the discharge at the electrode point was obtained, making use of a slit. This was carried out for aluminum, copper, and iron electrodes. In every case the presence of metal vapor was detected in the initial spark discharge starting the first half-cycle of arc-over, the aluminum showing up most intensely. Fig. 13 shows one of the moving film spectra obtained with an iron electrode. There were apparently two spark discharges at the start of the first half-cycle of arc, as two spark spectra of air are visible on the film there. Faint arc lines of iron can be detected in these first spark discharges while the succeeding eleven half cycles of flashover show arc lines of iron vapor only. Since iron vaporizes at 2450 deg. cent. it would seem that temperatures sufficient for thermionic emission at the electrode are probably reached at the very first spark breakdown of the gap. Other factors than heat may possibly come in, though, to facilitate vaporization during the first air spark, since the initial high-voltage gradient at the electrode may provide sufficient bombardment by positive ions, or strong enough electromechanical forces to remove metal particles from the electrodes which would in turn be vaporized. It is interesting, nevertheless, to find metal vapor present within the first one thousandth of a second of flashover.

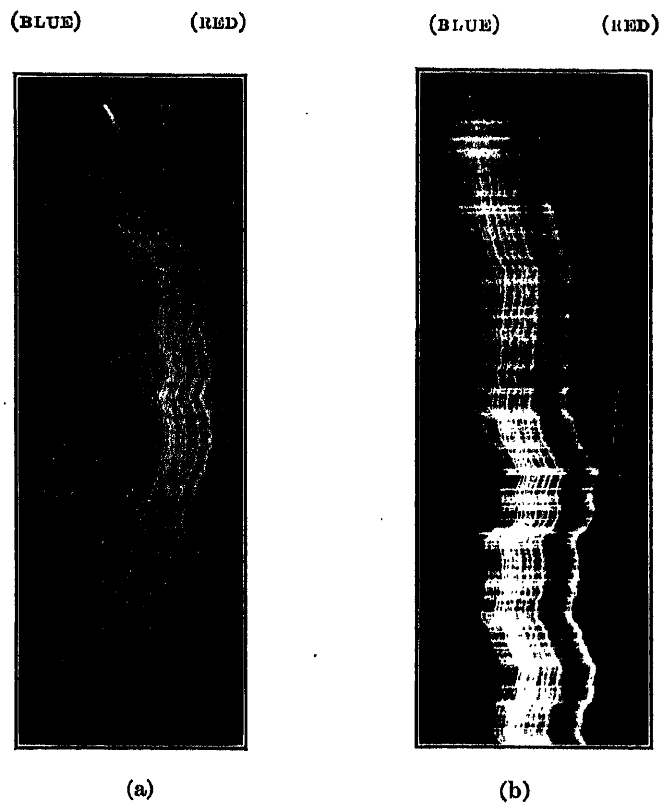

Fig. 12—Comparison of Laboratory Sparkover and Lightning Spectra

(a) Spectrum of initial spark bridging 10-ft. point-to-plane gap, which started first half cycle of complete 60-cycle flashover

(b) Spectrum of lightning stroke. (Fox-Yerkes Observ.)

It was not possible to secure a recognizable spectrum of the arc itself in the center of the gap after the first sparkover, due to its continually changing its path over each half cycle. The light intensity of the arc part of the flashover was not great enough either, with the spectrograph used and the distances that had to be maintained from the gaps, to allow of the use of a slit or of a rapid shutter action. Therefore, one was unable to determine whether the arc lines of air only would be present in the center of the gap after the first breakdown spark. No spark lines were found other than those of the initial discharge. In some short spectrographic exposures made of the 10-ft. flashovers though, it was apparent from the metal arc lines visible that metal vapors extended out from the electrodes an appreciable distance within the first two cycles of flashover, at least 8 or 10 in. in the case of iron, and about 6 in. with aluminum.

Spectrographs were taken of the positive and negative corona discharges prior to flashover, using a stroboscope. Exposures of about 20 sec. each were necessary in this, so that only that portion of the discharge next to the point remained sufficiently stationary to give a recognizable spectrum. Here the band spectrum of molecular nitrogen was found for both the positive and negative discharges, with no evidence of any oxygen radiations or metallic excitation. This is somewhat in accordance with the results of others.[10,11] This band spectrum is typical of the arc form and it was hoped that the intense white negative streamers might be shown to involve spark radiation spectra, at least at their outer high-voltage ends. Each was too brief in duration, though, to allow of analysis by spectrographic means.

THE PROBABLE HISTORY OF A HIGH-VOLTAGE A-C. FLASHOVER

Factors Involved. Undoubtedly ionization by collision, as originally suggested by Townsend and later amended by others,[12] plays an important role throughout an entire high-voltage a-c. flashover. At the start it is the essential factor in breaking down the air column between electrodes. Later thermionic emission and metal vapors enter to enhance the conductivity of the channel, the former giving its pure electron supply from the electrodes, while the other provides a much more easily ionized medium for conduction. Metal vapor is particularly favorable to high-arc conductivity for the following reasons:

1. It has from one-half to one-third the ionizing potential that such gases as oxygen, hydrogen, or nitrogen have, thereby requiring lower voltage gradients for maintaining a given current through it.
2. It does not become the electron trap that such

atmospheric gases as oxygen do, for oxygen tends to remove electrons by forming ions, thereby hampering the discharge.

3. Metal vapors have more elastic impacts than gases like oxygen or nitrogen, in that way removing less energy from the ionizing electrons when they strike.

Process of Breakdown. When the potential across a gap or over an insulator string becomes great enough, due either to the alternating voltage being increased, or an impulse wave superimposed, two corona streamers from opposite electrodes will meet and bridge the gap. (No experimental evidence yet has served to explain the exact details of this contact.) The condenser capacity of the electrodes and its attached parts will then discharge across, giving an intense initial spark. If, due to a too low applied voltage, the stored electrostatic energy ($1/2\, C\, E^2$) is not great enough to provide a sufficiently heavy discharge for starting adequate thermionic emission or metallic vaporization at the electrodes, the gap breakdown will cease, and the voltage wave will return to normal, similar to the one shown in Fig. 5. On the other hand, should the initial discharge be ample to create sufficient thermionic emission and metal vaporization at the electrodes, (and possibly a certain amount of sufficiently ionized and excited gaseous bodies in the gap), then the conductivity of the channel will be increased enough to allow the discharge to be maintained though the voltage wave continues to drop through the remainder of the half cycle, as seen in Fig. 1. On the next half cycle the discharge has to form again, but due to many of the particles in the gap being either already ionized or in an unstable state, it requires only a small voltage rise before the gap is again broken down, whereupon the voltage wave falls once more. As the arc-over current increases, which it surely must unless the effective applied voltage is dropped appreciably, less and less voltage is required to break down the gap each half cycle. Probably ionization by collision occurs at the beginning of every half cycle, although in a fully developed power arc, with copious thermionic emission and metal vaporization in existence, it would require but a small initial voltage for it to start the discharge each time. Thermal agitation and slight photoelectric effects probably enter to assist in the ionization process by "exciting" neutral bodies, but it is highly questionable whether they in themselves do any actual ionizing.

FIG. 13—MOVING-FILM PHOTOGRAPH OF SPECTRUM OF DISCHARGE AT IRON POINT ELECTRODE

Shows approximately 1 in. of 10 ft., 60 cycle, flashover to floor. Two brief discharges, each giving spark lines of air coupled with slight arc lines of iron, appear on the left at start of first half cycle of flashover. All eleven half cycles of flashover show arc spectrum of iron.

Fig. 14 is that of a photograph loaned by Mr. Harold Michener of the Southern California Edison Company. The main photograph shows a complete 50-cycle power arc. The insert in the corner is a fiftieth of a second exposure of the arc, taken after the latter had persisted for some time. This latter figure brings out well the tendency of each half-cycle discharge to develop its channel along the path of the rising ionized gases and vapors, however greatly distorted and lengthened this path may be. When the length of path becomes so great that its resistance drop exceeds the applied voltage, the arc will re-form along a new discharge channel at a lower point.

ACKNOWLEDGMENTS

Doctor Ryan suggested this study of flashovers and has been a valuable source of assistance and guidance throughout. Professor J. S. Carroll took part in all of the tests and is largely responsible for many of the results obtained. Mr. Bradley Cozzens of the laboratory staff also assisted in much of the work.

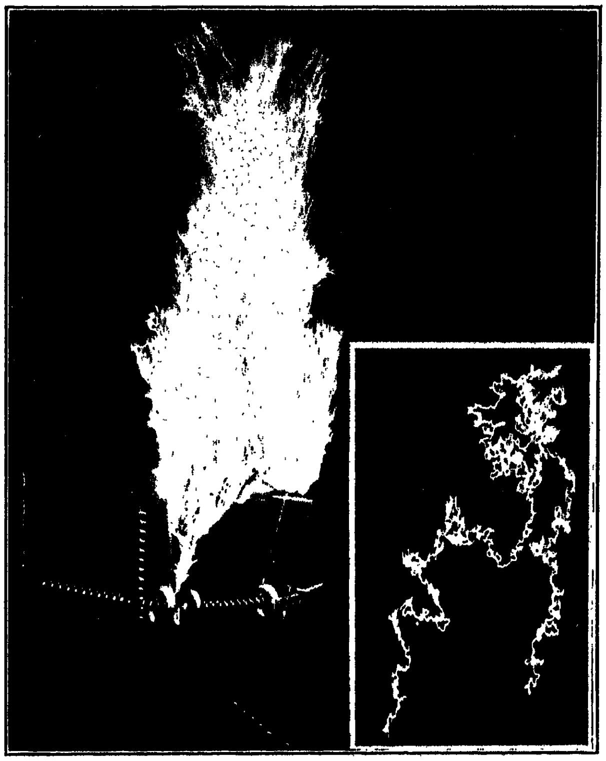

FIG. 14—TYPICAL POWER ARC ON TRANSMISSION SYSTEM

Photograph of complete 50-cycle arc on Southern Calif. Edison Co., with insert showing one-fiftieth second exposure of same

Doctor L. B. Loeb of the Physics Department of the University of California very generously helped the author to secure the facts regarding electrical breakdowns as known to physicists, and continually pointed out the meaning of many of the laboratory results obtained. Valuable assistance in the spectroscopic analysis of flashovers was secured from Professor F. S. Brackett of the University of California Physics De-

partment, and from Professor J. G. Brown and Dr. G. R. Harrison of the Physics Department at Stanford.

A subsequent paper involving the measurement of the flashover voltages themselves was presented before the Pacific Coast Convention of the Institute at Spokane, Washington, August 28-31, 1928 by Professor J. S. Carroll and Mr. Bradley Cozzens, page 1.

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Discussion

IMPULSE FLASHOVER OF INSULATORS

(TOROK AND RAMBERG)

A STUDY OF HIGH-VOLTAGE FLASHOVERS

(LUSIGNAN)

ATLANTA, GA., OCTOBER 30, 1928

T. F. Ball: Whereas Dr. Lusignan's paper has brought out and helped to clarify many of the phenomena pertaining to high-voltage flashovers, still I feel that in order to get a more complete physical concept of the phenomena involved we should take into account the effect of having the electrodes and the spark-gap itself exposed to radiations of different frequencies, under the same conditions of pressure and voltage between the electrodes. This, of course, would entail an application of the well-known quantum theory. For example, let us consider the case in which we have two pointed electrodes of copper, each having the same radius of curvature, and separated a certain distance d apart in air under normal atmospheric pressure.

If a d-c. potential be applied to the electrodes so that one becomes positive and the other negative, it is obvious that as the voltage is raised the neutral gas atoms in the space between the electrodes would become more and more distorted until finally the outermost electrons in the atoms would be moving in such eccentric orbits as to allow them ample opportunity for escape from their parent atoms. This, of course, would mean that these electrons, which have just broken away from the neutral atoms, would then be free to move under the influence of the electric field, thereby causing an increase in the ionization already begun between the electrodes. This cumulative effect would naturally persist until a rupture or flashover occurred.

Moreover, those free electrons, which are contained within the negative electrode, will have a tendency to be pulled across the surface of this electrode, and then under the influence of the strong electric field they would be drawn toward the positive electrode with considerable velocity. Hence, we see that these fast moving electrons would aid greatly in causing additional ionization in the space between the electrodes. Such an effect would be a contributing factor in causing the flashover to occur. Now, if the electrodes were more pointed it is obvious that less work would have to be done by the electrons in coming across the surface of the negative electrode, and therefore those electrons which escape from the surface would possess considerably more energy than formally. Those would tend, under the same conditions of pressure and voltage, to increase the ionization. Hence we see that a flashover would probably occur at a potential somewhat lower than when the electrodes had a larger radius of curvature. Such a supposition would be entirely in accord with a result obtained by Dobije when he made use of the theory of images to prove that an electron does less work in escaping from a curved surface than from a flat surface.

Let us now return to Fig. 1 and suppose that the gap and both electrodes were subjected to electromagnetic radiation of a definite frequency, such as ultra-violet light or X-rays. Assuming the frequency of this incident radiation as ν vibrations per second, and the amount of work done by the electrons in passing across the surface of the electrodes as w, then we would have

$$V e = h \nu - w \tag{1}$$

or,

$$V e = h \nu - \phi e \tag{2}$$

where V is the retarding potential across the gap, e is the electronic charge, h is Planck's constant of action, and ϕ the electron affinity of the metal, of which the electrodes are composed.

We see from the above equations that for any given set of electrodes, separated a certain distance apart in air of a definite pressure, and having a definite difference of potential applied between them, we would expect the energy of the electrons emitted from the negative electrode to possess energy characteristic of the radiation falling upon the electrode itself. That is, the higher the frequency of the radiation the more energy the escaping electrons would possess. Moreover, the neutral gas atoms in the space between the electrodes would certainly be in a more excited state as a result of the absorption of quanta of larger energy content. Both of these effects would favor ionization so that the flashover would occur at a lower potential than when the gap was subjected to radiation of lower frequency.

I noted from the results of Dr. Lusignan's paper that under the conditions of his experiment he found that when applying an a-c. potential to a point-to-plane set-up he always obtained a flashover on the half cycle when the point was positive. He gave as an explanation of this phenomenon the fact that the electric field was more concentrated around the point than it was in the neighborhood of the plane. While I concur with him in the explanation of his experiment as carried out, still I believe that it would be possible to obtain a flashover on the half cycle when the point was negative instead of positive, if the gap and electrodes should be subjected to radiation of considerably higher frequency, such as ultra-violet light or X-radiations.

Whereas Dr. Lusignan has shown that ionization, thermionic emission, and metal vapors all play an important role in causing an a-c. flashover between two metallic electrodes, still his results do not take into account the effect of the photoelectrons emitted from the electrodes themselves as a result of the energy absorbed from the incident radiation falling on the spark-gap. I believe that some valuable information could be obtained by carrying out Dr. Lusignan's experiments under the conditions which I have cited, *i. e.*, subject the spark-gap to high-frequency radiations. I would also suggest that the radius of curvature of the electrodes be varied through a wide range in order to see what effect the shape of the electrodes would have upon the flashover, for any particular frequency of radiation. I would further suggest that the spark-gap be enclosed so that the pressure of the intervening dielectric could be varied.

Furthermore, I feel sure that such information might be of considerable importance in arriving at the most economical size of conductors and the best type of insulators to be used on transmission lines in high altitudes. This would be especially true in the case of very high-voltage transmission lines where there is always a considerable amount of energy wasted in the form of corona.

J. T. Lusignan: The need for properly shielding suspension insulator strings was recognized with the advent of the higher line voltages some time ago. The experimental study of this problem was probably first carried out in the West at Stanford University under Dr. Ryan in the interest of the Pacific Coast power companies, and in the East by Dr. Peek at Pittsfield, both of whose work was reported to the Institute about eight years ago (A. I. E. E. TRANS., 1920). Soon afterwards the necessity for shielding against impulse flashovers was recognized and the laboratory work in connection with the study of this was reported at various times (F. W. Peek, Jr., *General Elec. Rev.*, 1923, V. 26; A. I. E. E. TRANS. 1923, 1924; *Journal Franklin Inst.* 1923.)

The paper by Messrs. Torok and Ramberg describes a similar study of shielding under impulse conditions, and the manner in which they have represented with curves the arcing characteristics of the various shielding arrangements (Figs. 11 and 12) is very interesting.

In this paper which deals essentially with insulator flashovers, several references have been made to the mechanism of the breakdown of air itself that are a bit misleading. The authors state: "The more homogeneous the field, the faster the streamers will develop, since under these conditions, higher gradients at the tips of the streamers are possible. For instance, the streamers grow much faster in the uniform field of a sphere-gap than in the non-homogeneous field of a needle-gap." Of course, once the breakdown is started in a sphere-gap the rupture is complete in an extremely brief time, but if a needle gap of the same spacing is in parallel with it the needle-gap breakdown should start and be over long before the voltage has started appreciable action in the sphere-gap.

I believe that experimental data bear this out, for on one impulse sparkover curve that I have seen a 1000-kv. wave of a fraction of a microsecond front will break down a 90-cm. needle-gap, whereas the maximum spacing of meter spheres that this wave will rupture is approximately 45 cm. It is true that with an increase in wave-front steepness the needle-gap spacing must be decreased for sparkover at a given crest voltage, but even for the steepest waves encountered in practise it can still be sparked over at an appreciably greater spacing than a sphere-gap.

The above 1000-kv. impulse wave will also spark over 7 insulator units of 5¾-in. spacing each, representing a total distance of 102 cm. This then would indicate that the suspension string is faster than the needle-gap. Accordingly, this would seem to be the reason for the string cascading with the arrangement of simple arcing horns. With the large ring shields though, the fields at the ends of the insulator string are appreciably altered and the stress concentrations around the end units so much modified as to lessen the "sparkover speed" of the units and allow the discharge to occur between ring edges.

The authors state: "It is obvious that a homogeneous field between the rings is desired to speed up the streamer formation. The nearer the surface of the ring approaches that of a sphere, the more uniform the field will be." How close they have come to a homogeneous field in their design is questionable, for the flashover of Fig. 13, and the longest streamer of Fig. 14 are both from the sharp edges at the ends of the ring sectors.

I should like to ask the authors what the ring spacing of Fig. 13 was and what voltage was necessary for flashover, also what method they used for calculating the rather smooth field gradient curves of Fig. 9.

D. H. Rowland: The paper of Messrs. Torok and Ramberg confirms a great many of the laboratory facts arrived at some time ago by Dr. F. W. Peek and used in the development of the grading shield, the merits of which have been proved by a great deal of field experience.

Surge investigations are yielding more and more information regarding the exact nature of disturbances on transmission lines. Before many of these data were available, it was found by laboratory experiments that an insulator string equipped with an arcing device which would clear it properly of impulses of very steep wave front would also function properly when subjected to longer waves down to those approaching ordinary 60 cycles. Moreover, it was found that arcing horns would not give satisfactory results unless the spacing between the horns was cut down so far as to reduce materially the 60-cycle insulation.

Some of the earlier grading-shield installations consisted of galvanized iron pipe, bent into an oval shape and placed at the bottom of the insulator strings, in conjunction with a pair of arcing horns at the top. Later a ring was also placed at the top of the strings. In this way, it was possible to prevent insulator breakage under all types of surges and at the same time not cut down the 60-cycle flashover more than 12 per cent. It was also determined that such installations would raise the flashover voltage of steep waves 10 per cent or more.

A ring at the top and bottom allows power arcs following the initial surge to blow around the insulators rather than through them. To accomplish this properly, it is important for the rings to be continuous and unbroken. The device shown by Mr. Torok is lacking in this respect.

The latest laboratory information which is available indicates that rings of flat strap rather than pipe give better flashover values under steep impulses. This is no doubt due to the dissipation of energy in corona by the sharp edges of the rings. It is fortunate that the strap rings are also cheaper to manufacture. Very satisfactory results in the field have been obtained by this type of equipment, of which over 50,000 shields are now in actual service.

In the light of our present information concerning the exact nature of the disturbances taking place on transmission lines, it seems best to let the design of insulator protective devices be a compromise between what is indicated by laboratory data, field experience, and manufacturing costs.

J. H. Cox: The particular importance of the papers by Torok and Ramberg, and Lusignan is the relationship they bear to the flashovers experienced on transmission lines in service, due to the actual surges existing on those lines. If we knew more definitely the nature of the surges with which we have to contend we could more intelligently apply these principles of protection, and furthermore proceed more efficiently with our laboratory investigations.

The klydonograph of Mr. Peters has told us much during the past five years regarding transmission-line surges. It has told us that switching surges are unimportant; that potentials subsequent to flashovers are unimportant, with the exception of those on isolated neutral lines; and that lightning causes all those surges which give trouble on a well designed system. It has given data on the number of surges encountered during one storm, the polarity of such surges, and their magnitudes, as limited by line insulation. What we now need to know is the more detailed nature of these surges; the shape of the front, the total duration, the shape of the tail, and the magnitude to which lightning surges may go if unrelieved by line insulation limitation. Torok and Ramberg's paper demonstrates clearly the influence the wave shape has in one particular instance of vital importance.

Several groups are working on this problem of determining the detailed nature of lightning surges. It has been known for some years that the cathode-ray oscillograph would be an ideal instrument with which to obtain the picture of a lightning surge, if only it could be set to catch the picture when the lightning stroke occurred. At least two methods of doing this are being tried. One of these, the Kipp relay, was developed in Germany, and consists of a vacuum tube arrangement to start the oscillograph after a surge arrives. The worst feature of this is the delay of about 1 microsecond in getting into operation and that much of the surge is lost. The other method, Dr. Norinder's invention, provides a means of placing a cathode-ray oscillograph in operation for two hours or more at a time, able to catch any lightning surge during that time.

Two Norinder cathode-ray oscillographs have been installed on the 154-kv. transmission line of the Aluminum Company of America at Chilhowee, Tennessee. To make the test as comprehensive as the facilities now at hand permit, these oscillographs have been supplemented by klydonographs. Also a scheme has been devised to record the position of the stroke. This record merely consists of a vibrating oscillographic record of the time difference between the arrival of the electrical disturbance and the sound of thunder. These stations have been in operation during the latter part of the past season.

Since the installation of the oscillographs only one stroke in the immediate vicinity of the oscillographs has occurred. From this one record was obtained. This record, together with a detailed description of the oscillograph, and the other apparatus of this installation, will be in a paper to be presented before this Institute in the near future.

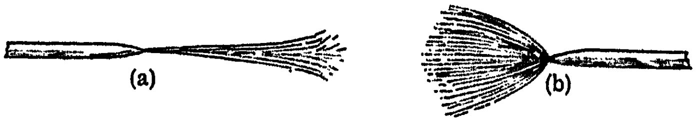
Klydonograph data indicated that very few surges per storm occur. Usually, there would be only one large surge and seldom more than two or three of any kind. This has been conclusively confirmed in this summer's tests. When I mentioned previously that only one stroke had taken place near the stations since the installation of the oscillographs, I did not mean in the general vicinity. Storms within sight and sound, and even near at hand, were rather frequent, and some caused fairly high surges at one of the outlying klydonographs. However, all but one caused no appreciable surge at the oscillograph stations. It seems to be a fact that in order to cause a surge of appreciable magnitude the lightning stroke must either strike the line directly, or within a few feet of the line, and then not far from the point of measurement. This means that to obtain the information needed we must work with very infrequent phenomena and that the work must be slow and expensive. Even with the klydonographs it has been an expensive proposition to place them as thickly as needed. Thus, the best efforts of the industry as a whole are necessary. Certainly the problem, while important to the manufacturer from the point of view of apparatus design, is even more important to the operating utility from the point of view of system design and operation. The problem is pressing and too large for any one firm or group to handle satisfactorily. Therefore, some form of coordinated effort by the entire electrical industry, including both operating utilities and manufacturers, is needed, and must be worked out. It is to be hoped that there will not be too long a delay for this cooperative effort to be effected.

L. E. Reukema: Doctor Lusignan's paper is a happy illustration of the engineer's increasing knowledge of the very extensive and valuable research of physicists, and of his willingness to make use of their results and, where applicable, to use their methods and the type of apparatus they have developed. At the same time it is a forceful illustration of the difference in magnitude of the quantities ordinarily investigated and measured by physicists and by engineers. Whereas physicists have been studying spark-gaps measured in inches or in fractions of an inch, Dr. Lusignan studies gaps of 10 to 22 ft., the voltages used increasing in a similar manner.

I have been particularly interested in seeking to explain some of the results reported. A physical picture, showing why the sparks occur as they do, should add to the value of the data obtained. For instance, Dr. Lusignan reports that an a-c. spark from a point to a grounded plane always occurs when the point is positive, yet a spark from one sphere to another grounded sphere always occurs when the isolated sphere is negative, provided the gap is not greater than the diameter of the spheres. At first thought, these results seem contradictory, yet a simple analysis enables one to predict exactly these results.

Flashovers, Point to Plane. Consider a positive point and a negative plane with the voltage between them gradually raised to the flashover point. Any electron or negative ion in the near vicinity will be attracted to the point, colliding with the air molecules and, as it approaches close enough to the point, attaining a speed sufficient to enable it to knock electrons (negative particles of electricity) out of these molecules, thus making the molecules positive ions. The electrons knocked out will also speed toward the point, knocking electrons out of the molecules they hit, the latter electrons ionizing in turn, so that for one electron originally attracted to the point many millions may hit it. The positive ions produced by the ionization are repelled from the positive point, and as they attain a high enough speed they may also knock electrons out of some of the molecules encountered. These electrons in turn ionize as they speed toward the point, this cumulative ionization resulting, in a small fraction of a second, in a flashover. The positive ions produced weigh almost 60,000 times as much as the electrons; therefore they cannot attain the speed in the electric field which the electrons attain. Since equal numbers of positive ions and electrons are produced, and electrons speed into the point faster than the positive ions can get out of the field, a positive space charge results.

This positive space charge so distorts the field that a potential between point and plane not quite sufficient to produce a flashover when the point is negative will cause a flashover when it is positive. Note from the accompanying Fig. 1 that the field at the positive point is such as to allow the field to build out as a pencil, whereas at the negative point the discharge is more fan-shape and extends out a much shorter distance. The reason for this is that between the positive point and a positive ion any space charge helps to speed the ion on its way away from the point, thus allowing it to ionize at a greater distance from the point than it could if the space charge were not there. A positive space charge between a negative point and a positive ion, however, can only slow the ion down, as the repulsive effect of the positive space charge subtracts from the attraction of the negative point. Similarly, the positive space charge between a positive point and an electron, when that space charge becomes increasingly denser as the point is approached, speeds up the electron, and thus increases its ionizing power, whereas the same charge between a negative point and an electron traveling away from the point evidently must slow the electron down. This explains why the corona extends out farther from a positive point than from a negative point for the same voltage. Since flashover occurs when the corona from the point extends all of the way across the gap, evidently a spark will take place when the point is positive at a lower voltage than when it is negative.



Corona from a positive point. Corona from a negative point.

Fig. 1

The space charge, together with the difference in mass of the electron and the positive ion, explains the difference in shape of the discharge from positive and negative points. The positive ion, being of the same mass as the molecules with which it collides, gives up a large part of its kinetic energy to the molecule at each collision, regaining velocity from the field between collisions and moving on the average in as nearly a straight line as possible toward the negative point or away from the positive point. The electron, on the other hand, is about 60,000 times as light as the molecules with which it collides. Therefore, it rebounds from such collisions retaining almost all of its kinetic energy, such rebounds in all directions effectually preventing an electron from following anything even remotely resembling a straight line. Remember also that a positive space charge tends to pull an electron into the densest part of the charge and that the positive ions forming such a charge violently repel each other.

In view of these facts, consider the ionization near a negative point. Electrons, ionizing as they move away from the point, are deflected in all directions, therefore the positive ions, produced by the ionizing of the electrons, approach the point from all such directions and the discharge is fanshape. At the positive point, positive ions tend to take as direct a path as possible away from the point and toward the plane. Therefore, the electrons resulting from the ionizing of molecules by these positive ions must start from some point near this straight line, and, in spite of the fact that collisions tend to deflect the electrons away from this line, the strong attraction of the positive ions concentrated along such a line tends to prevent the electrons from getting far away from it. Corona near a positive point, therefore, builds out as a pencil straight toward the plane.

Flashover between Spheres. Consider now two spheres, the lower one grounded, the space between the spheres being not greater than a sphere diameter. All of the lines of electrostatic flux leave the upper sphere, but only part of them end on the lower grounded sphere, the rest going to the ground. The potential gradient, being proportional to the electrostatic flux density, is therefore greater at the upper sphere than at the lower grounded one. If the gradient is just sufficient to allow ionization by positive ions at the upper sphere, it will, therefore, be insufficient to allow such ionization at the lower grounded one. Consider, now, what happens when an electron is either produced or strays into the field between the spheres. If the upper ungrounded sphere is negative, the electron is repelled from it and speeds into the lower sphere, ionizing as it goes, the resulting electrons continuing with it into the lower sphere and the positive ions produced moving up toward the upper sphere. The original electron, together with the electrons which it knocks out of the molecules with which it collides, may easily produce many millions of positive ions. Close to the upper sphere, where the gradient is greatest, some of these positive ions succeed in ionizing, thus starting a new stream of electrons toward the grounded sphere. These electrons produce more positive ions by collision and so on, this cumulative ionization resulting in a spark. Note that, though the gradient is sufficient for ionization by positive ions only when they are close to the upper sphere, electrons are able to ionize at the lower sphere also since their small mass and larger mean free path enable them to attain the ionizing speed at a lower potential than that necessary for positive ions.

Now consider the upper ungrounded sphere as positive and the voltage between spheres the same as before. An electron in the field will be attracted to the upper sphere, ionizing as it goes. Positive ions produced by such ionization will be repelled from the upper sphere. Those produced very close to the surface of this sphere may ionize while in this high field. However, the probability of ionization is small as the ions stay in this high field such a short time and are moving into a lesser gradient as they move away from the sphere. A few probably will ionize, but the electrons so produced are so close to the upper sphere that they have little chance to ionize more than once or twice before being pulled into the sphere, and the probability of the few positive ions produced by the latter ionization being successful in ionizing as they leave the sphere is negligibly small. At the potential gradient at which a spark takes place, the probability of ionization by electrons is many hundreds of times greater than that of ionization by positive ions. Remember also that the number of positive ions produced by an electron moving in a strong field is proportional to e (the base of the Napierian logarithm, 2.71828) raised to a power proportional to the distance which the electron travels. Therefore, if the electron in traveling a given distance can produce, with the help of the electrons which it knocks out of molecules, 100,000,000 positive ions (let us say), then in traveling half that distance it produces only the square root of 100,000,000 or 10,000 ions, and in traveling one-eighth of the distance it would produce only the eighth root of 100,000,000 or 10 positive ions. Evidently then an electron produced close to a positive sphere would have such a short path to follow that the number of positive ions it could produce would be too small to allow the cumulative ionization necessary to produce a spark. Therefore it is evident that a flashover will take place at a lower potential when the upper ungrounded sphere is negative than when it is positive.

All of this applies when the distance between spheres is not greater than the sphere diameter. However, when this distance is much exceeded, corona forms before the flashover. In other words, ionization takes place at less than flashover voltage and a space charge forms. When the space charge is present, the upper sphere acts as did the needle point, the lower grounded sphere and the ground together acting as the plane. There are then two opposing phenomena, the grounding of the lower sphere tending to cause the spark to take place when the upper sphere is negative, the space charge tending to cause it to take place when the upper sphere is positive, the result being that the flashover may take place for either polarity.

When Dr. Lusignan placed a 3/8-in. barb on the ungrounded sphere, the phenomenon was naturally that of point to plane and the spark always occurred with the ungrounded sphere (and the barb) positive.

The foregoing explanation also shows why flashover across an insulator string (of 10 to 14 units) always occurs on the half cycle when the conductor is positive, the phenomenon being similar to that of the point to plane. Corona forms before the flashover, forming a positive space charge and resulting distortion of field which speeds up the electrons and ions when the conductor is positive and slows them down when the conductor is negative.

Discharge Surges on Positive and Negative Half Cycles. Dr. Lusignan also calls attention to the fact that the brief discharge needles of corona at the ten-foot spacing between points, both points insulated, occur only on positive half cycles of current, and that they occur only when the voltage has almost reached the flashover point, and then occur several times each positive half cycle. At the 22-ft. spacing the same phenomenon occurs at positive half cycles, and in addition a very intense white discharge at intervals on a negative half cycle.

The phenomenon at the 10-ft. spacing may be explained easily by considering the relative mobilities of electrons and positive ions and the fact that chance has much to do with the amount of ionization occurring at any instant. Thus one electron together with all of the electrons which it produces as a result of ionizing collisions, may be responsible for (let us say) 22×10^{10} electrons arriving at the positive terminal in one surge. This would be equivalent to 40 ionizing collisions ($e^{40} = 22 \times 10^{10}$). Another electron in the same field might ionize fifty times, resulting in e^{50} or 47.5×10^{13} electrons surging into the positive terminal as a result of the ionizing activity of the particular electron considered and its progeny. Thus one electron may be responsible for 20,000 times as many electrons entering the electrode in one surge, as is another, and although 47.5×10^{13} electrons is small compared to 6.28×10^{18} (the number of electrons per coulomb) they enter the electrode in such a short period of time that, for an instant, they represent an appreciable current. Evidently in any positive half cycle several such extra large surges would be expected to occur, as the oscillograms show that they do.

That they would not be expected to occur on negative half cycles (for spacing of 10 ft. or under) is evident when one considers that the current at the negative terminal is due to the attraction of positive ions into that terminal. Since positive ions are so much heavier than electrons they move much more slowly. (At a gradient of 30,000 volts per cm., a-c., for instance, the positive ions would move 356.5 meters per second in the direction of the field, whereas electrons would move 121,600 meters or 340 times as fast.) The positive ions produced by one of the electrons ionizing fifty times, for example, as was considered above, would not be able to enter the negative terminal in one surge, as did the electrons at the positive terminal, but because of their much slower speed and the fact that their mutual repulsion tends to prevent them from concentrating close to each other, they would come in gradually, thus ionizing out the irregularities in their production.

The logical explanation, it seems to me, for the intense white streamers noticed occasionally coming from the negative terminal at the 22-ft. spacing is that, at the high potential necessary to almost spark across such a gap, the potential gradient at the needle point is almost sufficient literally to tear electrons out of the negative point. A dense positive space charge close to the negative terminal would of course increase this gradient, and when the space charge for an instant happens to be greater than normal or happens to have a peculiarly advantageous configuration, the critical gradient necessary to tear electrons out of the point is momentarily exceeded and an intense surge of current at that terminal results. Such an intense charge, lasting such a short time, could not be due to the relatively slow moving positive ions entering the negative point, but must be due to electrons leaving it and leaving it in far too large numbers to be due to ionization by positive ions.

W. S. Kates and E. D. Tanzer: In the discussions of wave shapes and specifications, Messrs. Torok and Ramberg note the impropriety of defining an electrical wave by merely giving the constants of the circuit producing the wave and the time taken for it to reach crest value. Their discussion states three factors and two of these factors are very intimately related to the amount of energy available in the impulse testing set. Later in the paper the formation of streamers and the movements of charges in the electrostatic field are discussed. It is a readily apparent corollary of these facts that the entire region surrounding an insulator string has its local potential distribution progressively changed by the application of electrical stress, and such application implies that energy is supplied to the region. It seems necessary, therefore, that careful consideration should be given to the amount of energy available in the testing set producing the wave to insure that this testing set produces discharge phenomena at all parts of the region of stress which are identical with those produced by a transmission-line traveling wave wherein the energy may be very much larger than that available in the testing set.

It has been our privilege to witness several tests with impulse generators at the different high-voltage laboratories at voltages of one million or more. The energies available at these laboratories in the various testing sets are of the order of 10,000 to 15,000 watt-seconds, at pressures of 2,000,000 to 3,000,000 volts. With these amounts of energies, it has not always been possible consistently to reproduce desired tests. The writers distinctly remember a proposed demonstration flashover of a 20-unit insulator string. Previous to the demonstration, the string had been repeatedly flashed over and the apparatus was left unchanged, supposedly ready for the demonstration. Repeated subsequent attempts to flash over the same insulator string were unsuccessful in spite of any adjustments made to the testing set in an effort to do so.

In view of the relation of the two factors to the energy available in the testing set, and the limitations of these sets, we should like to ask the authors what precautions have been used and what tests have been made to insure that the energy capacity of their testing set was large in comparison to the amount of energy required to fully charge the dielectric of the insulator string and surrounding regions to potential causing flashover?

Under "Break-down of Air" the formation and progress of streamers during break-down are briefly discussed and they have been further discussed in a previous paper by one of the authors. It is notable that the mechanism of breakdown which they discuss is dependent on a continuous supply of energy to the repeatedly growing streamer and, even previous to this, to the dielectric medium surrounding the insulator string.

The discussion of the components of forces acting on the streamers is especially interesting in that it is a corroboration of the principles stated by F. G. Baum in his 1921 paper before the Institute. The previous statement of the principle was that the potential of the insulator string must be higher than that of the surrounding air at all points or the arc would tend to strike toward the insulators.

On the fifth page it is stated that there is a definite relation between the mean diameter of the ring and cascading. This principle is visualized by Fig. 11. We understand that when a ring of a small mean diamèter is tested, the arcs will tend to strike toward the insulator string. As the mean diameter of the ring is increased, the tendency for cascading decreases and at some certain radius, all cascading stops. The radius at which cascading stops varies with the diameter of pipe of which the ring is made and an indication of the manner of this variation is shown in Fig. 4. Continuing this reasoning, we further deduce that if the mean diameter of the ring is further increased, a size will be reached at which the influence of a ring on the insulator string is small and cascading will again commence. In other words, the upper right-hand region of Fig. 11 noted as "no cascading" may not be a region. It would seem that a second line might be drawn, generally paralleling the curve of Fig. 11 and that only between this second line and the one shown is the non-cascading region. Accordingly, we should like to ask the authors whether they have made explorations of the territory shown as "no cascading" and, if so, would suggest that a discussion of this would be very valuable and pertinent.

S. Whitehead: (communicated after adjournment) I am very interested both by Dr. Lusignan's introductory and subsequent remarks as to the relation between spark and corona discharges and the arc. The work of Slepian and Compton has certainly made the distinction difficult and strengthened the view that the main differences is to be ascribed to the cathode fall of potential. I am, however, inclined to look at another aspect. Townsend's condition for discharge

$$\int \alpha \exp. \left(\int (\beta - \alpha)\, d x\right) d x = 1 \qquad (1)$$

(where α and β are the co-efficients of ionization by collision and the integral is taken over a line of force from electrode to electrode) enables one to predict the critical stress for corona when α and β are interpreted in a sufficiently general manner. This condition merely expresses the fact that ions must be generated as fast as they are removed from the field. In the arc, although such a condition must be obeyed, one is faced with the further difficulty of accounting for the high current density; whereas in corona, the magnitude of the currents can fairly well be provided by ionic and photo impact.

The spark, I am inclined to treat as follows: Equation (1) applies to corona in all its stages. At the beginning the field is not greatly modified by space charges, but as the voltage increases and the current and corona volume also increase, space charges come into play so altering the field and α and β that the condition (1) is satisfied. A point is reached, however, when the ionic density is too great for the condition to hold with the result that the left-hand side of (1), which is proportionate to the number of ions generated due to the passage of one ion from electrode to electrode, becomes greater than unity and the discharge changes into a self increasing type. Instability occurs and a large quantity of electricity passes until stability is again found under the new conditions of the arc and depending to some extent on the external circuit.

Thus spark may be looked upon either as exaggerated corona—if the condition prior to the sudden spark voltage drop is considered, or as an incipient arc—if the conditions after this voltage drop are examined.

The point at which condition (1) can no longer hold, however great the space charge due to the current, would correspond to the author's suggestion that the spark occurs when the corona streamers from the opposite electrodes meet.

The above views were suggested some years ago and later mentioned in a monograph[1]. A further suggestion made then with regard to polarity of discharges may be of interest—namely, that positive corona such as from a positive wire to a negative cylinder, is continuous with low-pressure discharges, but that negative corona under the same conditions is not, and, if the wire is kept negative, the low-pressure discharge will form at a voltage continuous with the original spark potential of the arrangement. This view was founded merely on the cathode fall[2] of potential theory and was supported to some extent by Crooker's observations. It has since been confirmed in the course of experiments on another subject by the British Electrical and Allied Industries Research Association.

As Wolcott[3] showed several years ago, stray positive flux concentrations even on dielectric surfaces will cause discharges to take place at the voltage corresponding to positive corona even though the main sharp electrode may be negative. I have myself noticed this effect with dry insulating materials though not so frequently if moisture is present and a surface film might be thought to be of importance. Perhaps the author may have noticed similar effects.

I would also venture to question to some extent the author's statement that in a fully developed power arc the restriking voltage is very small owing to thermionic emission and metallic vapor. My own opinion, which is supported by experimental work with which I have been concerned, is that in the majority of cases the effect depends almost entirely on the temperature of the space between the electrodes and the resulting density of the gas or vapor. Again, thermal ionization does not usually become important for the initiation of sparkover until very exceptional conditions occur. As to the effect of metallic vapor, such experience as I have with large power arcs has made me discount to a large extent the part which it is alleged to play in the restarting of an arc although, admittedly, if present, the majority of metals considerably reduce the sparkover voltage.

In this latter connection, I should like to mention recent work on the electrodeless discharges. That minute impurities in a gas affect its sparkover potential has been very clearly shown, but it also appears that they can be removed by the discharge itself. Thus it is possible that small quantities of metallic vapor may occasionally be removed by a small subsidiary discharge without restarting the arc.

With reference to the author's use of ultra-violet light, I should like to say that I have myself found that it has no effect on sparkover between spheres at atmospheric pressure—at any rate to an accuracy of ½ per cent. Further I have found no definite difference with certain different metals such as might be expected if a photoelectric effect came into play. Further experiments are, however, being made.

J. J. Torok: The questions of sphere-gap and needle-gap breakdown and streamer development are quite important. It is therefore necessary that their characteristics be well known.

In the case of needle-gaps, streamers start at a much lower value than between sphere-gaps. Then under a slowly rising voltage, a low-voltage breakdown can be expected for a given spacing. These streamers, however, grow very slowly permitting, under a rapidly rising voltage, a maximum potential difference of many times that of steady-state breakdown. On the other hand, when sphere-gaps are considered, this is not the case. Breakdown, or streamer formation, does not start, regardless of the duration of the voltage previous to breakdown, until the critical or breakdown value has been reached, then the streamers develop at an exceedingly high rate, thereby permitting the voltage to rise only slightly above the steady-state breakdown value.

The voltage at which streamers start to form, and their respective rates of development must not be confused. With this distinction in mind the statements, "The more homogeneous the field, the faster the streamers will develop, since under these conditions, higher gradients at the tips of the streamers are possible. For instance, that the streamers grow much faster in the uniform field of a sphere-gap than in the non-homogeneous field of a needle-gap, can be taken literally.

A good illustration of the above points can be made from a test on needle-gaps and sphere-gaps. A pair of 75-cm. spheres spaced 56 cm. apart were connected in parallel with a needle-gap having the same spacing. Under slowly rising voltages the needle-gap broke down every time, but as the rate of rise of voltage was increased a point was reached where "suppressed discharges" appeared between the spheres. Further increase in the rate of rise caused the sphere-gap to break down, leaving the space between the needles in a partially broken down condition.

The flashover characteristics desired for a line insulator are precisely those of a sphere-gap. Breakdown must not take place unless the potential reaches a fixed value, regardless of variations of the voltage below that point. If the voltage rises above that value, breakdown must take place in order to protect the power apparatus. Should the breakdown characteristics be that of a needle-gap, *i. e.*, allow an exceedingly high over-voltage to pass on, its protecting ability is reduced. Briefly, it is desirable that the insulator and its equipment have a flashover voltage, under even the steepest surges, equal to the 60-cycle breakdown value.

The ring shown in Fig. 13 was the final compromise between laboratory results, field requirements, and cost. The reasons for the large end sections are presented in the paper. The sides were made straight and located closer to the insulators because of the tower clearances on the particular line for which it was designed. However, it is to be noted that the active surface is unbroken, *i. e.*, an arc formed between rings can be blown from one side of the ring to the other with ease, the straps furnishing the path on the sides. The abrupt change in section is the result of a compromise between laboratory results and cost. The original design embodied a gradual change in section, but the cost became so prohibitive that competition with less effective rings was out of the question.

The experimental determination of field stresses was made with the straw-and-neon-tube method, which is described fully in the Hermsdorf Schomburg pamphlets Heft 19-20-21- and 22. The calculated curves were arrived at by methods fully described by Ollendorff. The old capacity method had been abandoned because of its inaccuracy. The Ollendorff method of calculation, however, is rather tedious.

The question of surge-generator characteristics as brought up by Messrs. Kates and Tanzer is of considerable importance, as the voltage wave that is impressed upon the insulator exerts more influence upon the final result than any other factor. The characteristics of the various types of surge sets in use cannot be analyzed in this discussion. The characteristics of an ideal surge generator will be presented and the properties of the other sets can be compared.

The ideal surge generator would have no inductance and very high capacity. It should be possible to vary the wave front and the nature of the tail. It should also be possible to maintain the crest potential for a long period of time.

Some types of surge generators produce a high-voltage pulse for only a fraction of a microsecond and the potential then drops to a low value. In many cases breakdown will be started at the high values and completed after the voltage has dropped to low values. Under this type of wave, breakdown is an unstable factor. Moreover, very little can be learned of the test specimens' characteristics, as the voltage is too variable.

The ionization currents during the period of breakdown often mount up to thousands of amperes, but their period of development is so short that the power taken is small compared to the capacities of large surge generators in use at present. The surge generator, then, must have an extremely low inductance to maintain the potential during streamer development. It is doubtful if such low inductance can be obtained with high-voltage surge generators.

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[1] "Dielectric Phenomena: Electrical Discharges in Gases," (Benn, 1927).

[2] Crooker, *Phys. Rev.*, 1906.

[3] Wolcott, *Phys. Rev.*, 1918.

The "no-cascading" area referred to by Messrs. Kates and Tanzer and shown in Fig. 11 was thoroughly explored by the authors. An outer limit has been found for the larger spacings, but the diameter of the rings necessary to reach that limit was so large that it was deemed unlikely that this region would be reached by any commercial ring.

J. T. Lusignan, Jr.: In reply to Professor Ball's question of the possible photoelectric effect on flashovers, we did not try any tests with light radiations of different frequencies except the short test on polarity alluded to in the paper. In view of the negligible effect of strong ultra-violet light sources on breakdown voltages in the laboratory as found by various experimenters (such as Dr. L. E. Reukema, A. I. E. E. Quarterly Trans., Vol. 47, January 1928, p. 38) I seriously doubt whether any atmospheric short-wave radiations should cause differences in flashover characteristics at different altitudes, as Professor Ball suggested might occur. He also asked about tests at different pressures. These were not included in our work, although such research, probably using at first monatomic gases and simple electrodes, would serve to supplement the work of the physicists at short spacings, and enable us to have a better understanding of high voltage breakdowns of long gaps.

I am greatly indebted to Dr. Reukema for his very clear and thorough analysis of the breakdown process in unsymmetrical gaps. He has given some very convincing physical pictures of the factors fixing the polarity characteristics of the various gap arrangements.

Mr. Whitehead has introduced a mathematical interpretation of the discharge processes, using an equation apparently derived from Townsend's original theorem. Such simple relations for depicting the breakdown process at a given point in space are surely helpful in expressing the relative activity of the various factors and bodies involved at that point, but just how such an equation could be extended to involve the complete discharge across the entire gap without becoming hopelessly involved and unwieldy is not clear to me. For instance, the breakdown between two points starts first as corona extending out from each electrode. These localized brush discharges are supposedly of a low-voltage nature and give the molecular band spectra typical of arcs. When these two apparently arc-like corona brushes meet, though, the complete breakdown across the gap involves a spark radiation spectrum extending from point to point (see Fig. 12) which afterwards probably reverts to an arc. The interpretation of these various stages of a flashover of a gap in air is difficult enough when attempted from a physical standpoint, without seeking to develop reliable mathematical relations to do it.

Mr. Whitehead objects to attributing the low restriking voltage of the arc principally to the presence of thermionic emission and metal vapors. I perhaps did not stress sufficiently the effect of temperature in lowering this voltage also, but I believe that most physicists discount the ability of heat to be the primary factor in most low-conductivity discharges. It is surely helpful, though, to know that Mr. Whitehead's particular experiments apparently indicate temperature and air density to be deciding elements in the discharge process.

Electrification of the Textile Industry in the Southeast

BY EDWIN M. CLAPP[1]
Non-member

and /

A. G. STANFORD[2]
Member, A. I. E. E.

Synopsis.—This paper deals with the subject from the standpoint of the public utility and the application of the electrical equipment in the mills, outlining the past and present practise with forecasts of the practises and developments of the future. Brief discussions are included of the advantages and disadvantages of purchased power over generated power and of the individual drive over the group drive. Statistical data are given on the percentage of the total spindles now operated on electric drive in the Southeast as well as the range of horse power requirement of various textile machinery and the cost per spindle for electrifying mills on various cotton products.

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Part I

The Relation of the Public Utility to the Textile Mill

BY EDWIN M. CLAPP

THE pioneer textile mill electrification in the Southeast was made at Columbia, South Carolina, in 1893. This was a hydro development, using horizontal water-wheel generators. About a year later one of the mills at Pelzer, South Carolina, put in a hydro development. This Pelzer unit was unique at the time, in that power was transmitted 2¾ mi. and employed a 3300-volt, three-phase transmission line. About two years later the Anderson Power Company at Anderson, South Carolina, was organized to supply power to the mills at Anderson. In 1904, the Catawba Power Company at Rock Hill, South Carolina, started operation, serving several of the mills in the vicinity.

In North Carolina there were many small hydro sites which were early developed. This accounts to some extent for the impetus textiles gained in North Carolina during that period. Most of these original installations were mechanical drive, later changing to electric drive.

In the earlier years about the only advantages electric power was thought to have had was the elimination of the main line shafting in the mill; or an opportunity to develop a water-power site which heretofore had been unusable. In the case of central station power, an opportunity to cut fuel costs.

It was not long before the advantages of breaking the load up into smaller groups to get additional economies were established, and that the savings in power costs were not the major reasons for electrification.

There were many obstacles to overcome in the early period of development. The machinery manufacturer, the manufacturer of electrical apparatus, the central station, the consulting engineer and the mill itself all had their problems to solve. In those days each factor worked out his own salvation irrespective of the others. Today these four have joined hands, and a problem that concerns one has the interest of all.

The troubles of the central station were possibly the most serious. Each company was small, with no interconnection or tie lines. High line transmission was far from what it is today and regulation none too good. In many cases the systems were over-sold, and droughts in the late summer and early fall necessitated shutdowns.

The phenomenal growth of the textile industry in the Southeast during the last fifteen years is known to nearly everybody. A contributable factor to this development has been the coordination of the activities of the manufacturer of electrical apparatus, the machinery manufacturer, the central station, and the consulting engineer in working out problems of application, illumination, and continuity of service.

The fact that there are only a few mills in the Southeast that are not using some form of electric drive is prima facie evidence of the desirability and advantages of this form of drive.

There are approximately 17,000,000 spindles in the Southeast today and about 75 per cent of these spindles are driven electrically. Approximately 80 per cent of the electrically driven mills are using central station power. It is in most cases cheaper, power averaging from 1.75 per cent to 0.75 per cent per kw-hr., depending on the size of the load. It does not necessitate using capital funds for non-producing and non-dividend earning machinery. It is much more flexible and does not put the mill at the mercy of the labor problems and physical hazards of the mining and transportation industries.

After a few years, many of the original hydro developments found their basins filling up with silt, thereby cutting down their storage capacity and lessening their prime power. The timber was being fast cut down, which meant quick run-off during rainfall. Practically all of these same mills found it expedient to increase their capacity, which, in most cases, the solution of the

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Presented at the Regional Meeting of Southern District No. 4 of the A. I. E. E., Atlanta, Ga., Oct. 29-31, 1928.

problem was purchased power. A great many mills came into existence that were not adjacent to a hydro site. These mills installed what were considered at the time very modern steam plants. The majority of these mills found it profitable to double up after a few years' operation and simultaneously awoke to the fact that their power plants were not only obsolete but inadequate to carry the additional load. Again the central station solved the problem.

A question that is very often asked and very seldom answered is, "Why are the textile mills in the Southeast standardized on 550 volts?" The answer is that in the early days the underwriters limited open wiring to 750 volts; 550 volts was the nearest standard to this limit, and also meant a tremendous saving in installation costs over 440-volt or 220-volt motors.

The textile load to practically all the utilities in the Southeast is a very large part of their production and the major part of the industrial load. The desirability of a load of this type plus the unusual increase in demand have kept the utilities busy in coping with this situation.

Today there exists a network of transmission extending over the entire Southeast, all tied in together. Practically all trunk lines consist of dual conductors, and nearly all primary feeders and distribution have tie lines, thereby insuring continuous service.

Interchange of power helps to work out a balance between hydro plants located on different watersheds, compensating for diversity in rainfall over different sections, and tends to equalize the delivery of prime power over a period of time between a high-head storage station and a low-head, stream-flow station.

A large block of high-economy steam reserve is ready for service on call. These steam stations are located at strategic points on the system.

In contrast to the over-sold condition existing a few years ago the utilities have anticipated the increase in load for several years to come, have worked out a program to meet these requirements, and today there is a comfortable surplus of power. As this power is absorbed new developments are made. From now on the supply will be ahead of the demand.

Large synchronous condensers are being placed in operation at different points on the system to insure better regulation.

Transmission problems are being solved. The research laboratories and personnel of the manufacturer of electrical apparatus are contributing very helpful service in working out these difficulties. The public utilities in the Southeast are doing everything that can be done to insure reliable service and to deliver low-cost power to their customers.

The textile load has always enjoyed a high-load factor, but the introduction of the individual drive with a large number of small motors usually operated considerably under-loaded has created lower power-factor conditions. Some of the central stations in this district are working on a bonus proposition for power-factor correction that will make it worth while for the mill to install the necessary corrective equipment. The day of purchased power on a kv-a. basis is not far away.

In bleacheries, dye houses, finishing plants and rayon plants, which require a large amount of process steam, an ideal form of electrification is the installation of a non-condensing steam turbine, the exhaust being used for manufacturing purposes and the balance of the electric load being furnished by the central station.

The central station realizes that it cannot grow and develop unless the communities and industries it serves are growing and expanding. Recognizing the fact that the Southeast is a logical place for the development of the textile industry, it has a corps of men working continuously in other textile centers to bring new textile industries into this section. The combined efforts of this activity have resulted in several hundred thousand spindles being located in the Southeast. This, of course, has resulted in direct benefit to the utility, but the indirect benefits gained by the communities in which these new industries have been located are far greater.

The field of development for the use of electric power in the textile industry is unlimited. The tremendous research facilities of the electrical manufacturer and the machinery manufacturer, together with the consulting engineer in the field and the central station are working harmoniously together to keep continuously improving their responsibility to the industry.

With these great forces joined together the prospect for electrical development in the textile industry is exceedingly bright.

Part II

The Application of the Electric Drive in the Textile Mill

By A. G. Stanford

In the preceding section of this joint paper reference has been made to the sources of power that were utilized in the early days of textile mill electrification. At this point it will be of interest to review briefly the types of drives employed in the earlier installations.

The first complete mill electrification was made in the Columbia Duck Mill, Columbia, South Carolina, in 1893, and consisted of 200-hp. squirrel cage, 40-cycle motors.

In 1894 the Pelzer Manufacturing Company, located at Pelzer, South Carolina, installed a 250-hp., 3300-volt, 60-cycle synchronous motor with other large 220-volt induction motors.

Soon afterwards the Anderson Cotton Mill of Anderson, South Carolina, wishing to eliminate as much of the overhead shafting as possible, installed eight-hp., water cooled, double shaft extension motors, each to drive two spinning frames, the motor bracket being so arranged as to tie the end of the two frames together and the motor shafts inserted directly into the cylinders. These motors were operated for some time in this manner but due to the difficulty experienced in maintaining the alinement of the frames, were later mounted on the ceiling and used similarly to the two-frame drive motors known today. This change was made after the first installation of four-frame drive spinning frame motors had been made in the Mayes Mill at Mayesville, North Carolina.

Limited by the then existing commercial designs of a-c. motors the large group drives were the logical consideration. These drives required the retention of a majority of the shafting and other mechanical idle load. The motors though sturdy and generous in design, were of low efficiency as compared with those of more modern design. The electrical losses added to the mechanical transmission losses resulted in an increase in the actual power required to operate the mills, together with an increase in some cases in the cost of power.

That the only principles applied in the first installations were fundamentally sound is witnessed by the fact that in comparatively recent years some of the installations made have followed largely the pattern of those installations which were made when the application of the electric drive to the textile industry was in its infancy.

With the view of reducing, as far as possible, the idle shafting load and to relieve the strain on the power plants occasioned by the use of the large size motors, the effort was early made to apply individual drives to a majority of the textile machines often through the medium of direct connection of the motor to the driven shaft. Many difficulties developed from this practise principally, in the case of the direct connected drives, to restricted range of speeds, and in general to inherent requirements of individual drive application to textile machinery which were not clearly foreseen at that time.

Like a pendulum the trend of textile mill electrification swung back strongly to the group drive but employing smaller units than in the earler installations. Special designs, such as the four-frame drive spinning motors were developed, which made it possible to eliminate heavy main line and countershafts and at the same time be free from the difficulties then encountered with the individual drives.

In later years, and even at the present time, the small group drive has retained a considerable amount of popularity, although, with the design of individual motors and controls perfected for practically every machine used in the textile industry, the application of individual drive motors is receiving more and more attention among owners and operators and is unquestionably gaining in popularity.

After the first few years of practical experimentation so much trouble was experienced with the control equipment, occasioning heavy maintenance expense, together with the problems of wiring and transmission of electrical energy, that for some time the progress of mill electrification was retarded until adequate improvements had been made in these items.

In 1906 the Profile Cotton Mill at Jacksonville, Alabama, decided on the use of a five-hp., 60-cycle, 550-volt motor to drive each spinning frame, the motor being direct connected to the cylinder. This application, though crude in many ways, as compared to the modern individual drive, was nevertheless a success and is still in operation using much of the original equipment.

In 1911 the Duncan Mills of Greenville, South Carolina, installed the most extensive application of individual drives then existing, this plant being individually driven throughout with the exception of the cards and roving. The spinning frame motors drove through pinions and gears to the cylinder.

In 1921 the Dixie Spinning Mill, now the Dixie Mercerizing Company, of Chattanooga, Tennessee, erected the first textile spinning mill in the United States to be completely equipped with individual drives. The success of this installation is evidenced by the fact that since the erection of the first unit three additions have subsequently been made and in each case the individual drive has been used throughout.

Ever since the first application was made the designing engineers of electrical equipment have been confronted with the problem of adapting their equipment for the operation of machinery which for many years had enjoyed a considerable degree of perfection in operation through means of mechanical transmission.

With the design of textile motors and controls highly perfected the manufacture of this equipment is largely a commercial problem. Much consideration is now being given to the various mechanical features in the equipment itself and in the physical application of this equipment to the textile machines. Great improvement has been made in the design of the motor bearings and many types of silent chains and other transmission equipment suitable for short center drives are available. The successful development of compact and inexpensive magnetic starters with push-button control stations has contributed towards the increased consideration given the individual drives.

INCREASED PRODUCTION

That an increase in production per spindle-hour of mill operation can be realized in the majority of cases with the electric drive, as compared with the steam engine and mechanical drive, is well recognized by those who have carefully noted the results obtained in plants that have discarded the steam power equipment. In a 30,000 spindle spinning and weaving mill on narrow sheeting, which has been electrified within the past year, an actual increase in production of seven per cent has been realized, of which percentage the owners have attributed five per cent to the electric drive and two per cent to the fact that the entire mill had been operated slightly under speed on account of the overloaded condition of the steam engine. Another similar mill of 13,400 spindles on wide sheeting has an annual increase in production of slightly over four per cent. Still another mill, which has come under the author's observation, is of 11,400 spindles on hosiery yarns, from which the records show an increase of approximately 3½ per cent since electrifying.

The foregoing examples indicate clearly the possibilities and these cases are of particular interest since no additional machinery was added and no changes whatever in the goods manufactured were made.

Satisfactory records are available from a large number of installations showing a range of from one per cent to as high as ten per cent increase in production. An average increase of three per cent may conservatively be expected between corresponding mills on steam and small group electric drive, and four to five per cent for mills on complete individual drive.

The reasons for the increase in production per spindle-hour of mill operation may be summed up as follows:

1. The greater speed at which the mill can be started up and stopped.
2. The greater flexibility in the operation of the several departments, enabling each to be run at its maximum production and to maintain a balanced output from the entire machinery organization.
3. A more constantly maintained speed at the value desired affecting not only the overall production but also the quality of the product.

In the textile industry, the speed at which the individual workers perform their duties does not have as great an effect on the output as is the case in numerous industrial activities where many parts must be handled before the manufactured article is complete. In the manufacture of textiles the production is largely controlled by the three factors mentioned above.

GROUP DRIVE VERSUS INDIVIDUAL DRIVE

From the standpoint of first cost only, either for a new mill or one to be changed to the electric drive, the group drive is considerably cheaper; however, this differential is considerably reduced in the case of a new mill where the cost of the shafting, belting, pulleys, etc., would have to be taken into consideration. No further explanation of the reason for the increased cost of the individual drive is necessary since it is evident that the cost per horsepower for motors, starters, and wiring increases as the rating of the motors decreases.

It has long been conceded that the individual drive is superior, and justifies itself from a first cost standpoint, for certain operations. For example, the picker room machinery, while performing only a preparatory operation, is readily adapted to the individual motor, while the elimination of the counter shaft and several large pulleys on the machine itself somewhat reduces the extra first cost of the individual drive.

In the author's opinion, the individual loom motor, is unquestionably a logical and superior application and practically no new weave mills have been equipped in the past few years and probably will not be in the future, with other than the individual motor drive on these machines. The few to be equipped with group drive have been controlled more from the standpoint of first cost than from lack of appreciation of the value of this application. The higher maintained speed and the similarity of operation of all of the looms, together with the freedom from variation due to unequal belt tensions, all contribute to a considerable increase in production and uniformity of finished product.

On account of the starting requirements the total connected motor horse power will be greater in the case of the individual drives, resulting in a lower plant load factor. However, any increase in the electrical losses occasioned by operating under these conditions is more than offset by the reduction in shafting and mechanical transmission losses. The newly developed double cage windings for squirrel-cage induction motors produce the high starting torque necessary for many textile machines without affecting the efficiency and power-factor characteristics after the motor has attained normal speed. This type of motor will permit of a reduction in the total motor horse power and reduce proportionately the cost of the individual drive.

In general the over-all power factor of the plant load is usually higher with the group drive than with the individual drive. In mills consisting mainly of small group drives power factors between 81 per cent and 86 per cent can usually be easily obtained, while for mills with individual drives the over-all plant power factor will usually vary between 75 per cent and 80 per cent, although the author has noted power factors as high as 85 per cent on this type of installation.

COST OF ELECTRICAL INSTALLATION

In Table No. 1 is given the actual cost per spindle to electrify textile plants, manufacturing cotton goods, together with the total connected motor horse power installed at the time each installation was made. This information has been compiled from actual records. The cost per spindle includes the cost of the electrical apparatus, power wiring, and lighting transformers installed complete, but does not include the cost of any substation or generative equipment, mill lighting system or low-tension feeders between the substation and the switchboard.

Variation in the cost per spindle of different plants on the same product and employing the same type of drives is occasioned by numerous factors such as the arrangement of the buildings and whether of one or more stories, all of which affect the cost of the wiring, while the number of spindles on the various machines being different in different plants affect to some extent the total connected horse power. Several of the items given in the table, cover additions to existing plants,

TABLE I

ACTUAL COST PER SPINDLE TO ELECTRIFY TEXTILE PLANTS MANUFACTURING COTTON GOODS

Y	Yarn mill	SW	Spinning and weaving mill
G	Group drive*	I	Individual drive throughout
IL	Individual loom drives	IS	Individual spinning drives
IT	Individual twister drives	Dr.	Drills
TC	Tire cord	Sh.	Sheeting

No. of ring spindles	Year installed	Goods mfg.	Type drive	Total motor hp.	Cost per spindle
12,000-Y	1923	40's-2 ply	I	1040	$4.13
8,000-Y	1926	28's-2 ply	I	650	3.00
19,000-Y	1927	60's-2 ply	I	1284	2.60
11,400-Y	1924	Hosiery yarn	IS-G	675	1.80
18,400-Y	1926	18's ply	G	1225	1.65
19,700-Y	1926	20's combed	G	1165	1.40
13,400-SW	1925	Wide sh.	G	1028	1.80
16,100-SW	1927	Narrow sh.	G	977	1.80
8,700-SW	1927	Dr-sh.	G	480	1.75
10,500-SW	1927	Dr-sh.	G	639	1.65
50,000-SW	1927	Narrow sh.	G	3139	1.63
30,000-SW	1927	Narrow sh.	G	1440	1.30
6,500-SW	1927	Dr-sh.	G	568	2.15
16,700-SW	1926	Towels and Merino yarn	G	1155	2.10
5,000-SW	1923	Narrow sh.	IL-G	335	3.65
13,600-SW	1923	Outing	IL-G	1027	3.56
14,400-SW	1923	Chambry	IL-G	900	3.05
8,400-SW	1926	Napped sh.	I	633	4.50
17,700-SW	1923	No. duck sh.	G	1437	2.05
12,900-SW	1926	No. duck	IT-G	1673	3.60
10,500-SW	1927	Duck	IS-IT IL-G	1062	3.90
14,200-SW	1925	Tire cord and Fabric	IT-IL G	1430	2.80
32,300-SW	1927	Tire cord and Fabric	IS-IT IL-G	2970	3.60
30,200-S	1927	Tire cord	IT-G	2864	4.37

*Items indicated as group drive include, in all cases, individual drive on the picker room machinery.

which cases usually are lower in installation cost than the original unit.

HORSE POWER REQUIREMENTS

In Table No. II is given the average horsepower requirement of various textile machinery and the horsepower rating of motors used for individual drive. Where a range of horse power requirement or motor rating is given for any item, the indication is that the machine may be constructed of more than one size or number of spindles and the nearest standard motor rating should be applied for any specific installation.

THE ELECTRIC DRIVE IS APPLICABLE TO ALL BRANCHES OF TEXTILE INDUSTRY

In dealing with the subject matter of this paper the author has necessarily given major consideration to those mills manufacturing cotton yarns and plain or coarse fabric, since the Southeast has long specialized in these products and has produced the major percentage of the total poundage of the United States. As far back as 1923 the Southeast produced 75 per cent of all of the duck (excepting tire duck and fabric), 77 per cent of the sheeting, 82.7 per cent of the denims, 91.5 per cent of the drills, and 93.2 per cent of the osnaburgs, together with various other percentages of all of the cotton textiles produced in the United States. In later years the percentages have increased and it seems but a short time ahead until all of the plain and coarse fabrics will be manufactured in this section.

What has been mentioned with reference to the value of the electric drive in textile plants manufacturing plain cotton goods, applies in an even greater extent to plants on woolen, silk, and rayon products, since increased production and uniformity of finished product is translated into increasingly greater profit as the value of the finished product increases. In the manufacture of knitted goods motor drives have been successfully applied to all machines.

TABLE II

Textile machine	Actual horsepower	Size motor for individual drive
Bale breaker	3/4-1 1/2	1-2
Vertical opener	5 1/2	7 1/2
Conveyor fan and condenser	4-12	5-15
Breaker—lapper—single beater.	6	7 1/2
Intermediate lapper	4	5
Finisher lapper	4	5
Card—40 in. revolving flat cotton	1	1 1/4
Card—wool—full roller breaker	2	3
Card—wool—full roller finisher	3 1/2	5
Sliver lap	1/2	1
Ribber lap	1	2
Comber, with aspirator	1 1/8	2
Drawing frame	5 to 6 deliveries per hp.	
Slubber	45 to 55 spin. per hp.	
Intermediate	55 to 60 spin. per hp.	
Fine frame	60 to 80 spin. per hp.	
Jack frame	85 to 95 spin. per hp.	
Spinning frame—ring	30 to 100 spin. per hp.	
Spinning frame—mule	100 to 150 spin. per hp.	
Spooler, 100 sp	1/2	3/4
Warper:	1/2	3/4
Twister	15 to 40 spin. per hp.	
Twisters—cabling	8-14	10-15
Slasher	3 1/2	5
Loom—light 40 in. automatic	1/3	1/2
Loom—heavy	1/2	3/4 and up
Loom—narrow on light silk	1/6	1/3-1/2
Winder—quiller	1/3-1/2	1/2
Winder—cap and butt—15 sp	3 1/2	5
Winder—cone and tube 100 sp	4	5
Brusher	3-8	5-10
Napper	4-8	5-10
Inspecting table	1/3-1/2	1/2-3/4
Quiller—silk, 40 sp	1/3	1/2
Winder—silk, 100 sp	1/4	1/3
Warp. Mill—silk	1/3-5/8	3/4

For bleaching, dyeing, and finishing plants, the electric drive has proved its worth and individual drives have satisfactorily been applied on practically all finishing plant machinery. Due to a lower operating load factor occasioned by the fact that many finishing machines do not operate as continuously as in the spinning and weaving mills, and because of the variable speed requirements the individual drive is especially desirable.

FUTURE DEVELOPMENTS

But little further improvement can be desired or expected in the motor and control equipment as now applied to textile machinery. There is, however, much that can be done, through cooperation between the textile machinery and electrical equipment manufacturers, with the view of making the motor equipment a more integral part of the complete machine. It is probable that many features in the design of the textile machinery, which are necessary from the standpoint of a belt drive, could be changed to adapt the individual motor equipment more readily and at the same time reduce the cost of the complete machine and drive. The future will undoubtedly see improvements along this line.

Other future developments will no doubt embrace many improvements along the line of automatic control and regulation of the electrical equipment which will govern, to a large extent, the operation of the machines and the quality of the goods produced.

Heat, electrically produced, for slashers and for mercerizing and finishing plants, as well as for the mill buildings, are now feasible and future developments will no doubt make these applications commercially practical realities.

Further improvements in power-factor corrective apparatus and motors having an inherently high power factor can be looked for in keeping with the increased interest manifested in load power factor.

Of particular interest to the textile and electrical industries, the public utilities, and the consulting engineers, is the ever increasing range of usages to which electrical energy is being applied throughout the textile industry. Aside from its importance as the motive power, such miscellaneous applications as the electric stop motions and signaling devices on individual machines, Klaxon and siren type horns for signaling the operators, electric calling and intercommunicating systems, motor driven drinking water systems, motor driven air compressor plants for cleaning, these being automatically controlled to maintain the required air pressure, and individual motor driven humidifier heads and air conditioning equipment may be mentioned, while good lighting is recognized as an income producing investment. In fact, it may safely be stated that electrical energy now serves a necessary and useful purpose, directly or indirectly, in some portion of all activities or operations in the textile industry.

CONCLUSION

The foregoing remarks should serve to stress the fact that the electric drive is the most logical type of motive power for all branches of the textile industry and that satisfactory motor and control equipment has been developed for individual motor drive on practically all machines. The degree of importance of the uniformity of the finished product as represented by the loss in value due to imperfect goods or seconds, the limiting factor of first cost and the age and type of machine should all be taken into consideration and carefully weighed in arriving at a decision to adopt the individual or the group type of drive for any specific machine.

With the constantly increasing interest in the Southeast as a logical location for plants manufacturing all types of fabrics and finished goods, electrification in the textile industry will ever be an interesting and fertile field for talent of the electrical engineers throughout this section.

Discussion

J. W. Fox: The cotton-mill man is primarily interested in continuous service, the maximum number of pounds from the spinner and the maximum product from a given investment at the least possible cost.

I want to impress the fact that this is the time to prepare to give him that continuous service during next summer's lightning storms. Whether it can be done by new protective devices or in other ways, steps should be taken now.

J. M. Oliver: Our transmission and distribution system covers a large area, and our system is interconnected with those of neighboring companies. We feel that we are doing everything within reason to keep apace with the development of the art to provide continuous service to our customers. The important load centers are provided with at least two, and in many cases more, sources of power supplied over different routes. The protective equipment is so arranged that if one line becomes faulty, it will be immediately isolated, leaving the other line or lines to continue supplying service. Line or equipment trouble causes only a momentary dip in voltage, lasting for only a fraction of a second. We have found no way to prevent these momentary voltage surges.

An analysis of the service to customers over different sections of the system indicates that at least 90 per cent of the interruptions which they suffered during the past lightning season were caused by these momentary voltage disturbances. The interruptions are the result of the operation of instantaneous undervoltage protective equipment on the customers' motors. Many of these undervoltage devices operate practically instantaneously when the voltage dips to from 50 to 80 per cent of normal. For several years some of the manufacturers have had on the market time-delay undervoltage devices. Most of our customers' motors are now protected with the instantaneous type undervoltage relays, and where the time-delay relay has been substituted, material improvement in service has been noted. The cost of substituting these time-delay devices for instantaneous relays is comparatively low, and the substitution certainly seems justified, in view of the improved service.

We have made a series of tests on textile-mill motors. These motors, operating under full-load conditions, were suddenly disconnected from the source of supply, and it was demonstrated that the voltage to the motor could be interrupted for a period as high as four seconds without any injury whatever to the motor or to the quality of the goods. I want to make a plea to manufacturers, to the salesman, and to the customer, to cooperate with us in providing this time-delay protection, which will eliminate those outages which now result from momentary voltage disturbances.

E. F. Pearce: It is needless to say that the power companies are intensely interested in giving the very best service to their customers that is humanly possible. We have been up against a very serious problem on this question of lightning service, and it was very forcibly impressed on us during July of this year. Under a normal year we disconnect from our lines about 6500 kv-a. of transformers that are damaged, either a coil is punctured, a bushing damaged, or the transformer may be completely destroyed.

From January 1 of this year until August 1, we disconnected 30,000 kv-a. of transformer capacity, and 22,000 of that was damaged during July. That gives a picture of what lightning does to the operating department and what their troubles are.

Aside from those difficulties, we have the momentary lightning surges affecting the undervoltage release equipment of all our customers, particularly on the line that is affected.

It has been my experience that a cotton-mill man will probably stand one or two interruptions a week and not raise a very loud complaint about it, but when he begins to get five and six in an afternoon, or ten in a day, he complains bitterly. We experienced that during July. We saw that we had to do something, and with the cooperation of Mr. Oliver's department and his assistant, Mr. Logan, we went to various types of mills and made specific tests on equipment. We made a thorough investigation of all the switchboard control equipment, the wiring, the number of motors on each circuit, the control equipment on each motor, and got a complete picture of the electrical equipment in various mills.

As Mr. Oliver explained, we went so far as to determine what effect the slowing down of the motor would have on the product and also what effect the returning voltage would have on the motor. We had one particular case where the mill owner said, "Why, that proposition sounds all right, but my machinery won't stand it. I have certain twisters in my mill that will shut down in 1 to 1½ seconds."

We decided, with the customer's permission, to make various tests. We found that the very worst machine would stand 4 seconds without any trouble to the motor or to the goods being produced. We, of course, don't want any relay equipment that will handle a 4-second interruption. In this particular case we have called for 2½-second time-delay relays and we are satisfied that there will be no trouble from that equipment. I think that in the majority of cases 1 to 1½ seconds will be satisfactory.

The power company is perfectly willing to do everything possible to further the installation of time-delay relays. If there is any mill that is in trouble, we want to know about it and we are very glad to make a complete survey of that mill. I ask the cooperation of the manufacturers' salesmen and the engineers in helping us to put across this proposition because it is going to be our only salvation.

The degree to which this time-delay relay should be applied in certain mills warrants a great deal of study. There is a question whether we should put undervoltage relays on switchboard equipment and also on motor equipment. Certainly the cotton-mill operators object to leaving the undervoltage relay off each individual motor for the reason that when they do have an interruption for any great duration of time, if there is no undervoltage relay, it is necessary for an operator to go to each control and take the motor off the line. For that reason, they are inclined to insist that undervoltage devices be put on each individual starter, but if that is the case, then we can apply the time-delay relay to that particular control device.

In this connection, I should like to relate a concrete case of the application of a time-delay relay. About two years ago, we heard that a big development was going to be made in our territory, and up to that time this particular customer had always put in isolated plants, had never purchased power. We got busy with the directors of the company and interested them in purchased power. In the meantime, the equipment had been bought with the idea of operating on an isolated-plant system. As a result, there was certain relay equipment on some synchronous motor-generator sets and one relay was very delicate. It would drop out at about 80 per cent normal voltage, causing innumerable complaints about shut-downs. This customer was blaming us for the class of service we were rendering. We inspected the equipment and made certain recommendations, but they replied that their equipment was all right; that it was our fault and we should improve our service. They went so far as to install a turbine. They operated that turbine part of the time and part of the time they used it as a stand-by unit. When a storm would come up in an afternoon, they would put that turbine on the line and wouldn't wait for our lines to go out.

After several conferences with them, we put the proposition up to them to install certain relays, the same thing that we had been trying to do for the past six months. We went so far as to tell them, "We will put this equipment in for you. If it does what we say it will do, you pay us for it. If it doesn't do what we say it will, we will take it out and you haven't lost anything. You can go on with your turbine and disconnect from us entirely."

Finally the equipment was installed on that basis. It has been operating now for eight months and during July of this year that customer had only two shut-downs and if this relay equipment had not been installed I believe that he would have had over a hundred shut-downs during July.

As a result, he is entirely satisfied with our service. The service today actually is not better than it was before but the results were accomplished by the installation of those little relays that cost him, I think, $225.

George Wrigley: I should like to pledge our help, so far as we can, on this time-delay undervoltage protection. There are still some developments to be made, but it should take care of a great many interruptions. We ask that the power men also please do not neglect the other interruptions.

The mill man can be approached in all fairness and asked to pay for these things without their costing him anything at all. It is just a matter of where he puts his money. He can put it here or put it in losses of shut-downs because these interruptions are extremely expensive. I should like to carry the development forward on that basis.

Power Limit Tests
on Southeastern Power and Light Company's System

BY S. MURRAY JONES[1] and ROBERT TREAT[2]
Associate, A. I. E. E. Member, A. I. E. E.

Synopsis.—The general subject of stability and power limits has been discussed several times before the Institute. Most of the papers have been of a theoretical nature, presenting methods by which the power limit of a system could be calculated, or describing various schemes by which the power limit could be increased. Some papers have been written describing tests on miniature systems and a few, giving the results of tests on actual high-voltage systems on the Pacific Coast.

Calculations and tests on small models have indicated that power systems at or near the theoretical power limit could not be operated safely, since any slight disturbance would cause instability with the resultant separation of the power transmission system. Very often, tests on small models do not closely check the results obtained on the real system: therefore, as a result of certain troubles which occurred on the Southeastern Power and Light Company's System in 1925, apparently due to instability, it was decided to attempt to determine by actual tests the amounts of power which could be safely carried over certain transmission lines, and to compare the results with the calculated values. The General Electric Company offered to cooperate with the engineers of the Southeastern Power and Light Company in conducting such tests, and made them of further value by suggesting experimentation with certain schemes of high-speed excitation which could be applied to the generator excitation systems, in an effort to increase the maximum power limit which could safely be carried over the transmission lines.

This paper presents the results of these tests and the conclusions to be drawn from them.

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1. INTRODUCTION

THE Southeastern Power and Light Company serves a territory of considerable size and extent, covering practically two and one-half states. These states are Georgia, in which the Georgia Power Company operates; Alabama, which is served by the Alabama Power Company; and Mississippi, which is supplied by the Mississippi Power Company. The primary transmission system of these companies is operated at 110,000 volts. Previous to the consolidation of these individual companies into the Southeastern Power and Light group, 110,000-volt interconnections, for the exchange of energy, existed between them, the most important ties being between the Alabama Power Company and the Georgia Power Company. The two principal tie lines, and the ones on which these tests were conducted are shown on the map of the Southeastern Power and Light Company systems at the time of test, Fig. 1. During the fall of 1925, there existed a very serious water shortage in Georgia and the Carolinas, which, of course, limited the output of the hydroelectric plants in this territory, and would have necessitated curtailment of power to many industries had it not been for the system interconnections. The Alabama Power Company was more fortunate in having a normal amount of water for that season of the year, and sufficient steam reserve capacity to be able to deliver power over the two tie lines into the Georgia system, some of it being relayed into the Carolinas. The result of this situation was that the two tie lines on which the tests were conducted were loaded to capacity.

The Gadsden-Lindale tie line, which will be called the north line, was designed to carry economically a load of approximately 30,000 kilowatts, and the North Auburn-Newman, or South line, approximately the same amount. During this emergency condition, these lines each carried instantaneous amounts of power up to 50,000 kw., and during the 24-hr. period, an average of 40,000 kw. per line. The transmission losses and the voltage drop over the lines were high, but the power was needed and economics were temporarily forgotten. Unfortunately, the worse lightning occurs during the dry season, and with the lightning came more trouble than was expected. Several interruptions occurred on these tie lines for seemingly unaccountable reasons, and when one tie line would open, the other would immediately follow it.

The Martin Dam plant of the Alabama Power Company was not in active service during that year; hence, there were some 300 miles of transmission line between the Alabama Power Company's plants at Lock 12 and Mitchell Dam, or the government plants at Wilson Dam and Sheffield, and the Georgia Power Company's plants in the Tallulah Falls district in Northeast Georgia as will be seen from Fig. 1.

In order to secure the proper relay protection on these lines during light load conditions, it was necessary to set the relays to operate on values as low as 60,000 kv-a. This, of course, was close to the amounts of power which were being carried over each line during the times of peak load. Therefore after one or two interruptions in which both lines opened, it was at first supposed that the first line was tripped out due to lightning, and the second followed because of overload. However, patrol, and detailed inspection reports, failed to reveal any of the customary indications of insulator flashovers on either line, and a further check of the location of the storm at the time of the interruption

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[1] Southeastern Engineering Company, Birmingham, Ala.

[2] General Electric Company, Schenectady, N. Y.

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served to indicate that the storm was not over either tie line.

Hence, it was decided to obtain more detailed and accurate information at the time of the next interruption, which was expected, and did occur shortly afterward. During peak load conditions, the relay settings on these lines were increased to approximately 100,000 kv-a. and patrolmen and operators were notified to obtain all the information possible on the storm location and any insulator flashovers.

The result was that at the time of the next case of trouble, the cause of the interruption on these two tie lines was definitely determined as being due to instability. A lightning storm occurred south of the plant at Mitchell Dam which flashed over an insulator string on the Mitchell Dam-Lock 18 line, and tripped this line; at the same time, the two tie lines came out, one after the other. Thus it was proved conclusively that these tie lines had opened, first one and then the other, owing to the fact that the limit of power which they could carry had been passed.

At the time of the flashover on the Mitchell Dam-Lock 18 line, there was no more power going over these lines than prior to the short circuit. However, owing to the short circuit, the voltage on the entire system was reduced, and the voltage on the Alabama end of the tie lines was so low that the amount of power which the South line was carrying exceeded the power limit of the line at that voltage. Thus, the Alabama and Georgia plants were pulled out of step and both lines had to open to separate the two systems.

Numerous conferences resulted between engineers of the power company and of several manufacturers relative to methods of calculating the safe power limit of the lines. The calculations involved many indeterminates and assumptions, but finally seemed to indicate that the maximum amounts of power which the lines could carry and still not be subjected to interruptions caused by flashovers on other parts of the system was in the neighborhood of 25,000 kw. per line. This was not even up to the amount of power which the lines had been designed to carry normally, and, consequently, study was given to methods of increasing the power which could be transmitted over them safely. These studies included synchronous condenser installations, faster relaying on the tie lines and other parts of the system by means of carrier-current pilot wire protection, and the speeding up of the excitation systems on the generators at the various plants. The last method,—that of speeding up the excitation systems on the generators,—seemed to be the most logical, and was by far the most inexpensive.

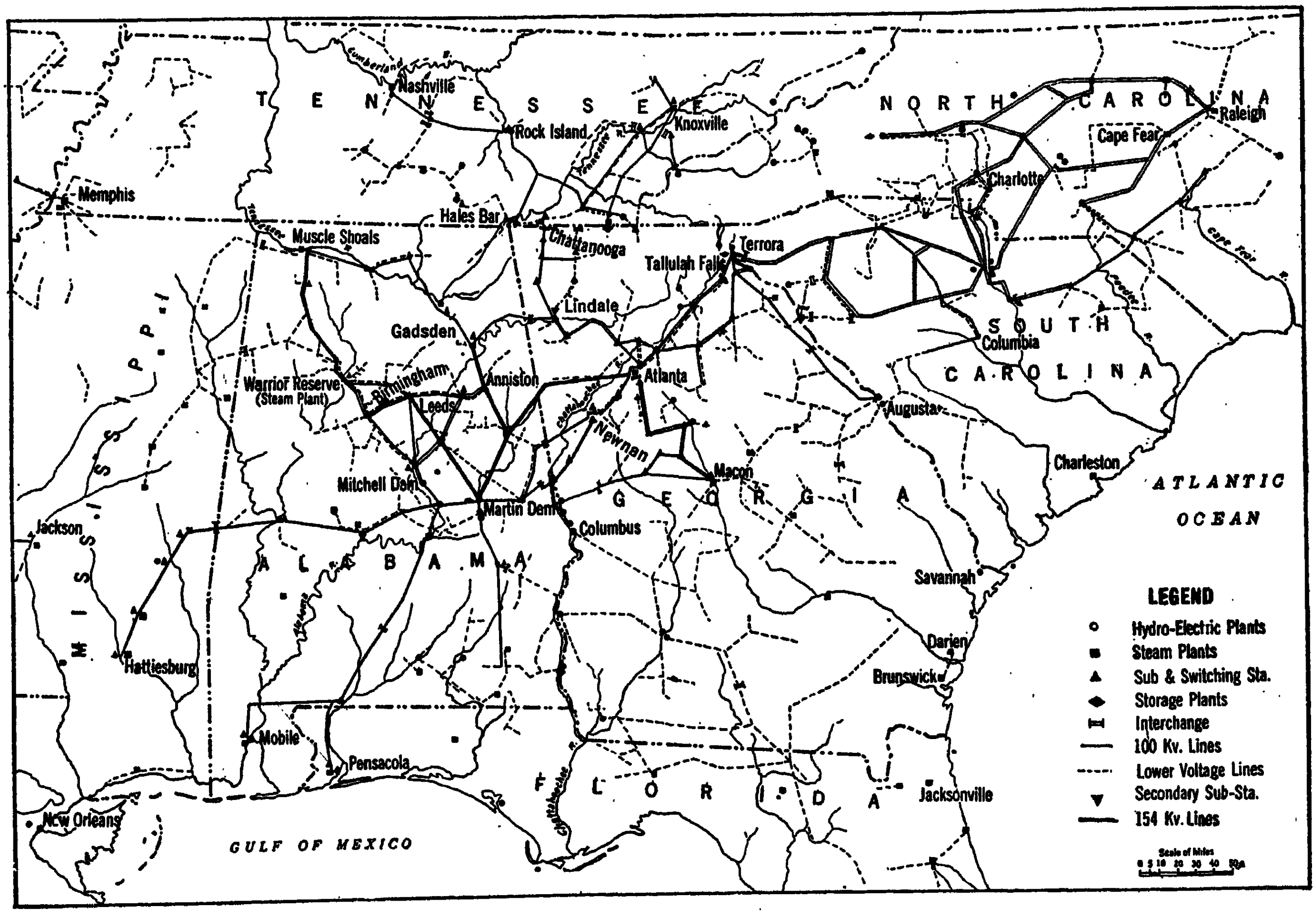

FIG. 1—MAP OF SOUTHEASTERN POWER & LIGHT COMPANY SYSTEM

After many discussions between the engineers of the General Electric Company and the Southeastern Power and Light Company, it was found desirable to make certain tests on these tie lines during the spring of 1927. The Alabama Power Company's plant at Martin Dam would then be completed and it was hoped that water conditions would be such that the Georgia Power Company would not require much power, thus making available for test the plant at Martin Dam and the tie lines. During the month of June, there was sufficient water at the Georgia plants to carry the Georgia load with practically no interchange over the tie lines, and as a result, the tests were made at that time.

II. Description of Tests

As progress was made in perfecting detailed plans for the tests, it became evident that it would be very desirable to broaden materially the scope from that originally intended. Particularly did it seem appropriate while making such tests to ascertain the beneficial effect, if any, of increased exciter build-up speeds and of new types of regulators which were then being developed. The final objective therefore may be summarized as follows:

A. To obtain the maximum power limit of the south line (test line) as a check on the value predicated from calculations. Particularly was a check desired on two items: first, the assumptions on which calculations were necessarily based, and second, the methods employed in carrying out the calculations. Such data were best determined with Martin Dam alone connected to the test line, whereby the added complication of interconnection of the Alabama Power Company's system was avoided.

B. To determine the maximum carrying capacity of this line under normal operating conditions with Martin Dam connected to the Alabama Power system.

C. To obtain information as to the efficacy of various kinds of regulators including the standard regulators installed at the plant and on increased speeds of exciter build-up. For the latter purpose, it was deemed desirable to compare:

1. Fixed excitation
2. Standard regulators and exciters as installed
3. New regulator in conjunction with
   a. Standard exciters
   b. Exciters arranged for increased speed of build-up.

The comparisons indicated under C were desired not only for steady-state operation, (*i. e.*, with no transients or disturbances on the system), but also for the condition of suddenly applied loads such as obtained when the north line was tripped and also during short circuits nearby on the system.

Three distinct kinds of test were therefore decided upon:

a. Steady-state pull-out between Martin Dam and the Georgia system both with Martin Dam alone connected to the test line and with Martin Dam and the test line connected to the Alabama system. For these tests when Martin Dam was connected to the Alabama system, the north line remained open.

b. Suddenly applied load by loading up the two tie lines in parallel and then tripping the north line to determine how much load could thereby be shifted to the test line without causing loss of synchronism. For this test it was expected to obtain points both above and below the value causing instability in order to determine as accurately as possible the maximum value of load which could be thus transferred.

c. Short circuit, obtained by closing a 110-kv. bus-tie oil circuit breaker at Martin Dam on a line-to-neutral short circuit of predetermined duration. The short circuit was made on the line side of the oil circuit breaker between one phase and the station ground bus and therefore contained practically zero resistance. Tests involving short circuits were made with the north line open, but with Martin Dam both isolated and connected to the Alabama System. These tests were to determine the maximum power which could be transmitted over the test line during disturbances exterior to the test line itself without loss of synchronism.

With the following methods of excitation it was expected to make all these tests on the generators at Martin Dam:

a. Fixed excitation
b. Standard exciters and regulators as installed
c. New regulator controlling the standard exciters
d. New regulator controlling the standard exciters arranged for high speed excitation.

After considerable study, the best means for attaining high-speed excitation on these exciters which are inherently of very low-speed build-up, appeared to be the following method: The exciter fields which consist of 10 poles, normally connected in series, were regrouped to give five parallel circuits, and were separately excited. Energy for separate excitation was secured from the auxiliary 550-volt power-house circuit, converted and regulated by means of thyratrons, the grids of which were controlled by the regulator. Arrangements were made for securing approximately 400 to 500 volts per second. Some tests were taken with the transformers on a half-voltage tap, giving about half that rate of rise.

III. Test Procedure

General Order of Tests. A total of approximately 50 tests was scheduled, but 31 were actually made, and these furnished practically all the data desired. Because most of the tests had to be made during the peak-load periods, and also because no testing could be done during lightning storms or other troubles on the system, no definite schedule could be adopted more than three or four hours in advance. In addition, it was felt that the results of one test might necessitate others not contemplated, or might eliminate some proposed. As work progressed, several tests were eliminated, since data obtained indicated such tests to be unnecessary.

In order to obtain the data with different speeds of exciter build-up, it was necessary to make major changes in the generator excitation systems. These changes involved considerable time and in order to facilitate the work on the generators and reduce the time of testing to a minimum, the tests were grouped according to the types of excitation used.

The first group were those using the normal excitation from the direct-connected exciters furnished with the generators, but with different types of voltage regulators. Steady-state tests, dynamic tests, and those involving suddenly applied loads, and short circuits were made. The steady-state tests were made first with the generators at Martin Dam isolated from the Alabama system and connected only to the test line; and second, with the test line tied in with the Alabama system. After completing this program, the connections of the exciters were changed for the so-called high-speed excitation. First an exciter voltage build-up of approximately 250 volts per second was used; and then 400 volts per second.

Equipment Used. One, two, or all three of the 37,500-kv-a. waterwheel driven generators at Martin Dam were used on each test. Those tests, requiring additional generating capacity, were made by tying the test line directly to the system 110,000-volt 'bus at Martin Dam. The load was the normal commercial load of the Georgia Power Company.

The test line was a 110,000-volt single circuit from the Martin Dam plant in Alabama to the Boulevard Substation near Atlanta, Georgia. The characteristics of this line are as follows:

Total length, 139.8 mi. (224 km.)
Total resistance (R), 41.5 ohms per conductor
Total inductance (L), 273.3 millihenrys per phase to neutral
Total capacitance (C), 1.957 microfarads per phase to neutral

The line contained three different types of construction as described below:

A. *Martin Dam—North Auburn.*
Length, 26.92 mi. (43.3 km.)
Towers, H-frame wood poles
Spacing, 17 ft. (5.18 m.) horizontal
Ground wires, 2 1/0 A. C. S. R. Conductors
Insulation, Locke 5800, 10-in. disk, 7 units
Size conductor 397,500 cir. mils, A. C. S. R.
R—6.33 ohms
L—56.8 millihenrys
C—0.3715 microfarads.

B. *North Auburn to Georgia State Line.*
Length, 40.4 mi. (65 km.)
Towers, H-frame wood poles
Spacing, 14 ft. (4.27 m.) horizontal
Ground wires, 2 1/0 A.C.S.R. conductors
Insulation, Locke 5800
Size conductor, 397,500 cir. mils, A.C.S.R.
R—9.5 ohms
L—82.5 millihenrys
C—0.574 microfarads.

C. *Georgia State Line to Newnan.*
Length, 30.22 mi. (48.3 km.)
Towers, wood pole H-frame and Steel "H" Frame
Spacing, 13 ft. (4 m.) horizontal
Ground wires, none
Insulation, O. B. 25622
Size conductor, 397,500 cir. mils, A.C.S.R.
R—7.052 ohms
L—61.3 millihenrys
C—0.4304 microfarads.

D. *Newnan—Boulevard.*
Length, 42.29 mi. (68 km.)
Towers, double-circuit steel
Spacing, 9 ft. (2.74 m.) vertical, 15 ft. (14.57 m.) horizontal
Ground wire, none
Insulation, O. B. 25622
Size conductor, 2/0 hard drawn copper, 7-strand.
R—18.62 ohms
L—92.7 millihenrys
C—0.582 microfarads.

The map (Fig. 1), shows geographically the location of the test line, the plant at Martin Dam, and the Boulevard Substation, also the Gadsden-Lindale line which was used on the tests in which load was suddenly dropped. Fig. 2 is a single-line diagram of the test circuit showing the switches with their numbers and the metering equipment on the south line used to obtain the readings and oscillograms. This line, as may be seen from the diagrams, constitutes one of the important tie lines between the Alabama and Georgia systems.

For obtaining the test data, oscillographs, and portable laboratory type indicating meters were located at Martin Dam, and graphic meters were installed at Gadsden, Newnan, and Boulevard. Six oscillographs containing a total of 21 elements were set up at Martin Dam in the cable terminal room directly beneath the switchboard room. The oscillographs consisted of four standard three-element machines, one special wattmeter oscillograph and one six-element instrument containing three single-phase wattmeter elements. The reason for so many oscillographs was that they were set up to obtain duplicate results, since, previous to the test, it was unknown just how accurately the point of instability could be determined. Consequently, on the first tests, one group of oscillographs were started as the pull-out point was approached, and if these did not record the actual pull-out, the second group was started. Experience during the first two or three tests indicated that the approach of the pull-out point was readily determinable and on all further tests, one master switch was used to start all the oscillographs at one time and duplicate films were obtained. The indicating wattmeters, voltmeters, ammeters, and power-factor meters, were arranged on a table in the terminal room, between groups of oscillographs.

The graphic instruments installed at other points on the system merely as a check, were as follows:

Newnan—Voltmeter, wattmeter, ammeter, and power-factor meter.

Boulevard—Voltmeter.

Gadsden—Voltmeter, wattmeter, and power-factor meter.

Procedure of Making Tests. Due to the uncertainties in the testing schedule previously mentioned and the relatively large personnel actively engaged in conducting the tests, conferences were held two or three times each day to discuss the previous results and definitely schedule the tests to follow. This proved very satisfactory and as the work progressed, eliminated many tests which were found unnecessary thus saving considerable time and duplication of effort. These conferences also resulted in a minimum disturbance to the system, which of course was most desirable.

During all tests, telephone communication was maintained between one of the men reading the portable instruments in the test room, who also had control of the starting switch for the oscillographs, and the supervisor of the tests who was located in the plant switchboard room. Continuous telephone communication was also held between the plant superintendent at Martin Dam and the chief load dispatcher of the Alabama and Georgia systems.

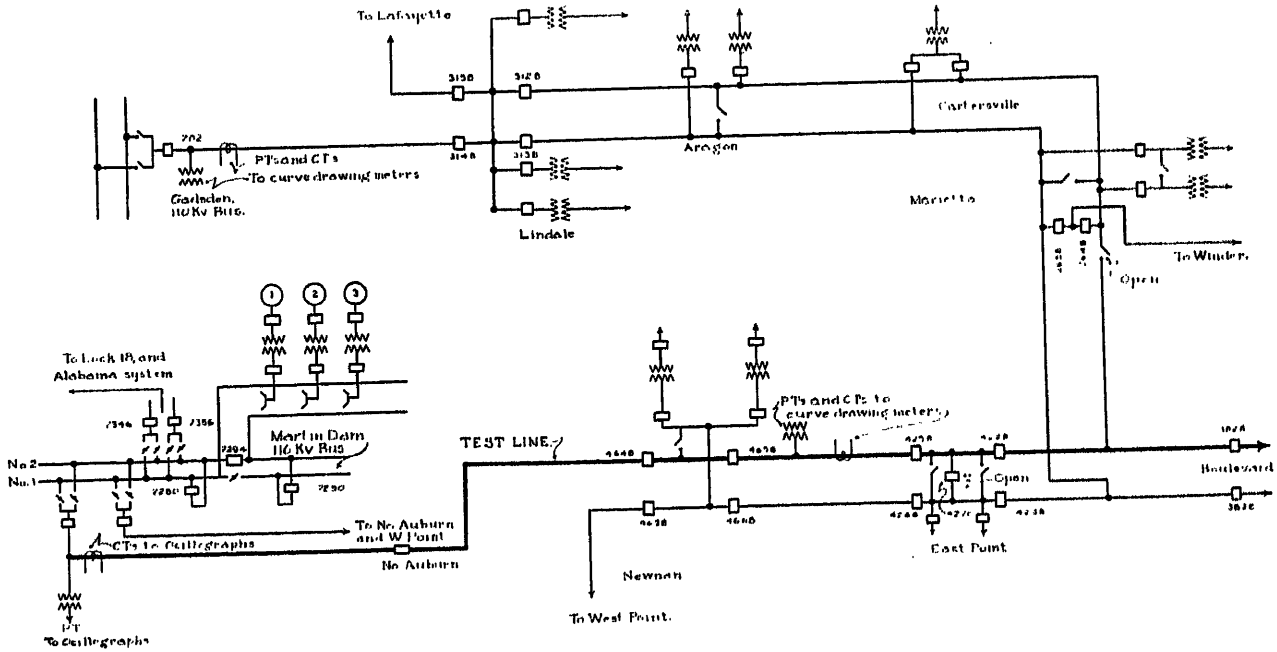

FIG. 2—SYSTEM CONNECTIONS FOR POWER LIMIT TESTS

One of the plant operators was stationed at the switchboard, and was directed by the supervisor of tests as to when to clear the test line after pull-out. Relays were used on the clearing switch, but they were given a relatively long time setting in order to insure complete data being obtained on the oscillograms. Had the relays been used to clear the line, in most instances the period in which the equipment was out of step would have been longer than necessary to obtain complete data, and therefore would have prolonged the system disturbances. The net result of this arrangement was that practically no complaints were received from customers of either company, and the only effect that the tests had on the operating system was that in one or two instances a rotary converter in Atlanta lost its synchronism and fell out of step. During all of the tests, there was no load lost.

In making the steady-state tests, the procedure was as follows: When all the oscillographs and system connections were ready, the chief oscillograph operator notified the supervisor of the tests, and he in turn notified the plant superintendent to request the Georgia dispatchers to drop a certain amount of generation. This load was picked up either entirely by the generators at Martin Dam, or by these machines and the Alabama system, depending on whether the tests were being made with the system tied in or not. The load on the test line was gradually built up to a point within 5 or 10 per cent of the calculated pull-out point. The voltage was then adjusted to as near 110,000 volts as possible and the power factor as close to unity as practical. Finally, with everything in readiness, the Georgia dispatcher was notified to drop load rapidly, and this in turn was picked up by the Martin Dam machines until the unstable point was reached. The circuit was cleared at the direction of the supervisor of tests after he was notified that the oscillographs had obtained the record of the pull-out phenomena.

On those tests in which load was suddenly dropped, the test line and the north tie line were loaded to a total load equal to that calculated to make the test line unstable when the north tie line was tripped. This necessitated another link in the telephone facilities and during these tests, the plant superintendent at Martin Dam gave orders over the phone to three parties; the Alabama and the Georgia dispatchers and the man stationed at Gadsden to read and report on the power over the north tie line. As the proper load was reached, the oscillographs were started and the man at Gadsden directed to trip the Lindale line immediately. If the test line failed to become unstable or appeared to reach instability too rapidly the tests were repeated with a slightly larger or smaller load as the individual case dictated.

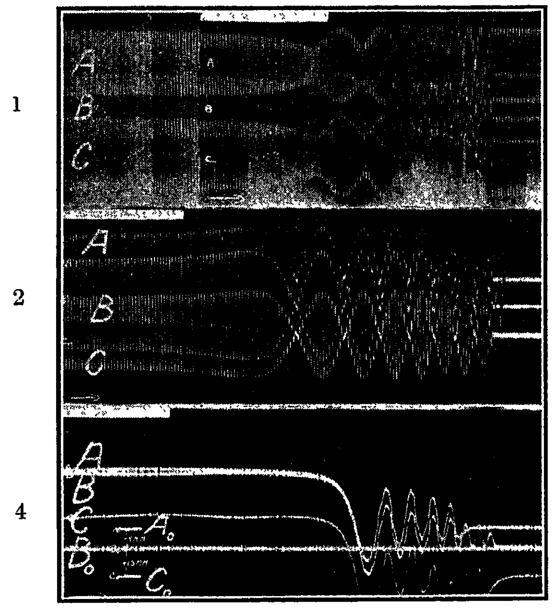

Fig. 3—Test No. 10. Steady-State Pull-Out of Test Line

Film No. 1—Line-to neutral volts on Martin Dam 110-kv. bus
Film No. 2—Current in test line
Film No. 4—Curve *A* Power, generator No. 2
Curve *B* Power in test line
Curve *C* Power, generator No. 3

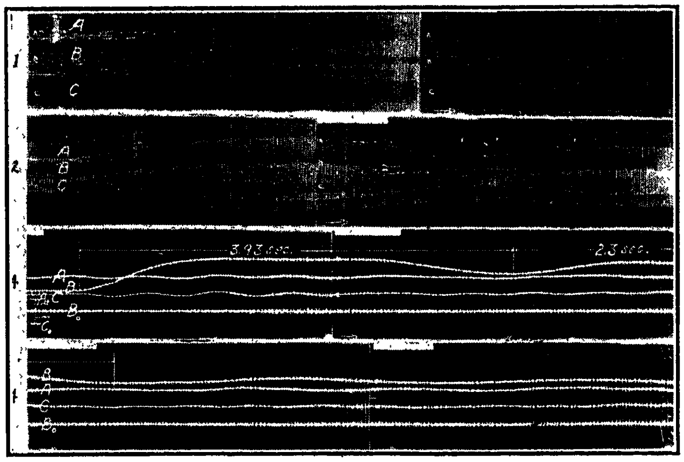

Fig. 4—Test No. 7B. Suddenly Applied Load by Tripping North Line; Synchronism Maintained

Film No. 1—Line-to-neutral volts on Martin Dam 110-kv. bus
Film No. 2—Current in test line
Film No. 4—Curve *A* Power, generator No. 2
Curve *B* Power in test line
Curve *C* Power, generator No. 3

The short-circuit tests were relatively simple and consisted of grounding one phase of the Martin Dam 110,000-volt bus by closing one of the bus tie oil circuit breakers on a previously made short circuit. The short-circuiting switch was closed by the plant operator on orders from the supervisor of tests immediately after the load on the test line had been adjusted and the chief oscillograph operator had notified him that the oscillographs had been started.

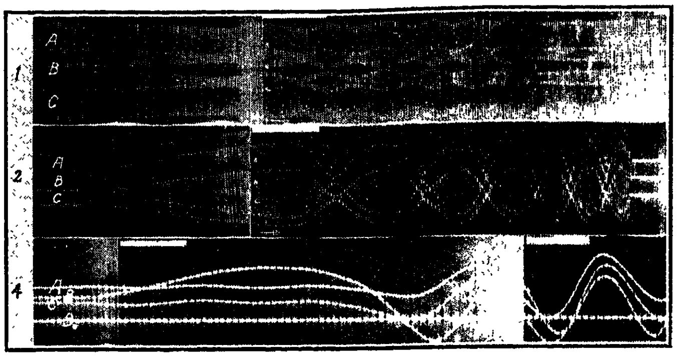

Fig. 5—Test No. 5B. Suddenly Applied Load by Tripping North Line; Synchronism Lost

Film No. 1—Line-to-neutral volts on Martin Dam 110-kv. bus
Film No. 2—Current in test line
Film No. 4—Curve A Power, generator No. 2
Curve *B* Power in test line
Curve *C* Power, generator No. 3

Dark room facilities were arranged in the plant, and practically all of the films were developed immediately

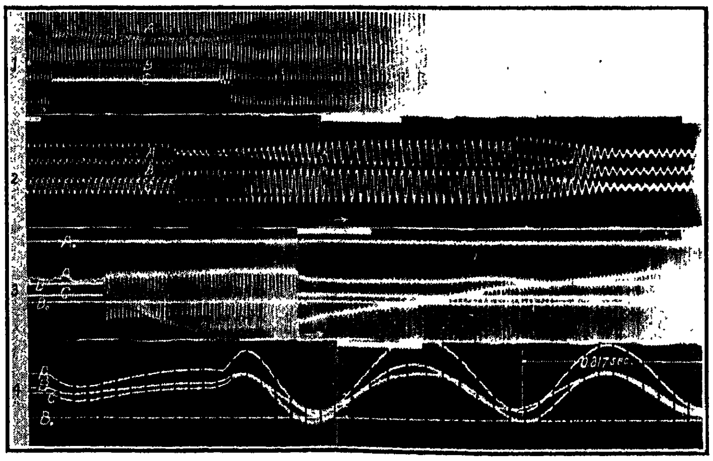

Fig. 6—Test No. 25A. Line-to-Ground Short-Circuit Test with Alabama System not Connected; Synchronism Maintained

Film No. 1—Line-to-neutral volts on Martin Dam 110-kv bus
Film No. 2—Current in test line
Film No. 3—Curve *A* Generator, slip-ring volts
Curve *B* Generator field current
Curve *C* Short-circuit current

Film No. 4—Curve *A* Power in test line
Curve *B* Power, generator No. 2
Curve *C* Power, generator No. 3

following each test. Thus, if for any reason the films were unsatisfactory, the test could easily be repeated.

IV—Curves and Tables of Results

The results of the tests are presented in the form of curves and tables. In addition, there are included reproductions of some of the oscillographic records, Figs. 3 to 9. From these oscillograms, it is possible to obtain a very comprehensive qualitative idea of the phenomena accompanying the disturbances set up by the various tests. The oscillograms of power were obtained on a three-unit instrument, each unit of which consisted of a three-phase assembly of wattmeter elements. One of the elements recorded power input to the test line; the other two, the power output of two of the Martin Dam generators. The moving part of these elements contained considerable inertia. The records of the tests for steady state pull-out and for the increase in power when tripping the north line are probably fairly accurate, since power changes in the test circuit were not very rapid. Owing to the inertia of the elements, however, the oscillographic record of power changes during the short-circuit tests are not entirely satisfactory. In analyzing the test data, therefore, it was necessary to make suitable correction of the values shown by the oscillograms to allow for the effects of inertia and damping. A check on the power input to the test line was obtained from the records of the single-phase wattmeter oscillograph.

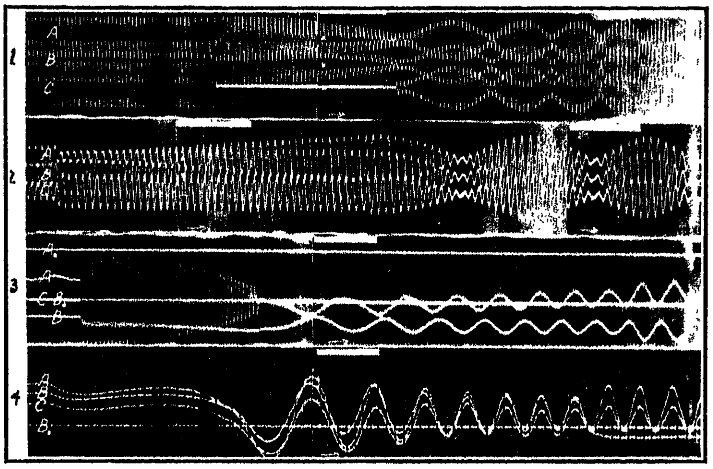

Fig. 7—Test No. 15B. Line-to-Ground Short Circuit Test with Alabama System Disconnected; Synchronism Lost

Film No. 1—Line-to-neutral volts on Martin Dam 110-kv. bus
Film No. 2—Current in test line
Film No. 3—Curve *A* Generator, slip-ring volts
Curve *B* Generator field current
Curve *C* Short circuit current
Film No. 4—Curve *A* Power in test line
Curve *B* Power, generator No. 2
Curve *C* Power, generator No. 3

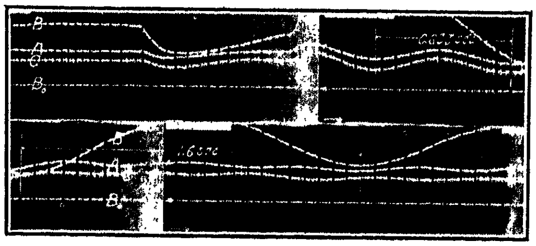

Fig. 8—Test No. 30B. Line-to-Neutral Short Circuit Test with Alabama System Connected; Synchronism Maintained

Curve *A* Power, generator No. 2
Curve *B* Power in test line
Curve *C* Power, generator No. 3

Table I presents the values of power obtained in steady-state pull-out with Martin Dam alone supplying the test line. For the sake of comparison, there are also included values of power calculated for the test line, plus the terminal apparatus with fixed excitation on the generators and at the values of terminal voltage observed in each test. In Table II are shown the corresponding values of power at steady-state pull-out with the Alabama System connected. As a means of comparison, there are also included in this table, values which it is estimated from the test data, the power would have attained at 110 kv.

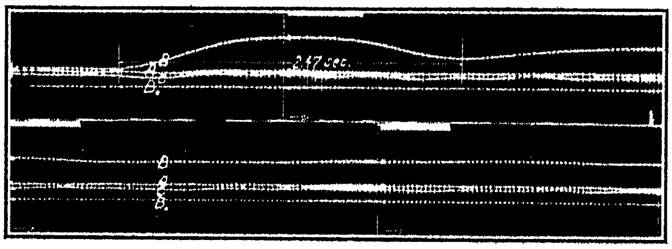

Fig. 9—Test No. 23B. Suddenly Applied Load by Tripping North Line; Synchronism Maintained

Curve *A* Power, generator No. 2
Curve *B* Power in test line
Curve *C* Power, generator No. 1

Table III gives the results of the tests in which a line-to-ground short circuit was thrown on the 110-kv. bus at Martin Dam, and for comparison, an estimate of the same values corrected to 110 kv. Table IV includes the results of tests in which the north line was tripped and the corrected values for 110 kv.

V. Comparison of Tests and Calculations

One of the purposes of making the tests was to obtain a check on some of the basic assumptions necessary in carrying out mathematical computations of power limits. It is therefore interesting to compare the values obtained from the tests with values calculated for the same conditions. Such a comparison for the steady-state pull-out with only Martin Dam connected to the test line is given in Table I. In the test with fixed excitation on the Martin Dam generators, a value of power equal to 98 per cent of that calculated for similar conditions was attained. This agreement is

TABLE I

STEADY-STATE POWER LIMIT WITH MARTIN DAM ALONE CONNECTED TO TEST LINE

Test No.	Excitation	Kilovolts		Megawatts		Ratio test to calc.	Test megawatts as percentage of maximum for line alone
		Martin Dam	Atlanta	Test	Calc. for same E_g and E_r		
8	Form Y—Std. exc.	109.98	95.26	93.6	82.3	1.137	73.6
9	Form K—24 exc.	107.90	95.26	90.6	80.6	1.124	73.7
10	Hand control	106.86	99.76	78.6	80.2	0.980	62.5
18	Form W—250 V/sec.[1]	112.75	95.60	104.5	90.9	1.150	79.8
21-A	Form Y—500 V/sec.[1]	103.92	99.24	97.4	75.4	1.292	80.5
21-B	Form W—500 V/sec.[1]	109.98	93.87	93.0	83.6	1.112	74.5

1. See text page 9 regarding thyratron grid control

TABLE II

STEADY-STATE POWER LIMIT WITH ALABAMA POWER SYSTEM CONNECTED TO MARTIN DAM AND TEST LINE

Test No.	Kilovolts		Megawatts		Excitation	No. gen. used at Martin Dam
	Martin Dam	Atlanta	From test	Corrected to 110 kv.		
1	107	96.2	90	106	Hand control	2
2	111	101.	104	112.3	Form Y std. exc.	2
3	110	102.	102	110	Form W std. exc.	2
4	110	102.	97.2	104.9	Form K—24 std. exc.	2
19	112	96.	104.5	117.6	Form Y 250 V/sec.[1]	3
22	108	101.	102.7	113.8	Form Y 500 V/sec.[1]	3

1. See text page 9 regarding thyratron grid control.

TABLE III

MAXIMUM POWER PRIOR TO LINE TO GROUND SHORT CIRCUIT THAT COULD BE CARRIED WITHOUT LOSS OF SYNCHRONISM

Test No.	No. Martin Dam machines	Line kv.		Estimated maximum power in kw.		Duration of short circuit in seconds	Volt-sec. rise during 1st. half swing of gen.[1]	Excitation
		Martin Dam	Atlanta	From tests	Corrected to 110 line kv.			
Alabama System not connected to test line								
11	2	102.5	105.0	28,000	31,450	0.857	−35.6	Hand control
12	2	103.0	105.0	28,000	31,300	0.882	−34.9	Form K—24 std. exc.
14	2	103.0	105.0	29,000	32,400	0.832	−20.8	Form Y—std. exc.
15	2	102.4	105.0	32,000	35,900	0.815	+12.7	Form Y 250 V/sec.[2]
16	2	102.0	105.0	32,000	36,100	0.807	− 2.0	Form W 250 V/sec.[2]
17	2	101.0	104.5	32,000	36,600	0.807	− 0.7	Form Y 250 V/sec.[2]
25	2	114.0	104.0	39,500	40,300	0.825	+49.3	Form Y 500 V/sec.[2]
26	2	115.0	102.8	48,000	49,000	0.608	+31.2	Form Y 500 B/sec.[2]
27	2	114.0	103.0	55,000	56,000	0.433	+43.9	Form Y 500 V/sec.[2]
29	1	114.5	103.0	22,500	23,100	0.915	−35.0	Form K—24 std. exc.
31	1	114.0	102.7	23,000	23,700	0.907	−35.0	Form K—24 std. exc.
Alabama System connected to test line								
24	2	112.0	101.5	55,000	58,500	0.682	+12.2	Form Y 500 V/sec.[2]
30	2	113.0	101.0	52,500	55,700	0.682	−16.7	Form K—24 std. exc.

1. See Appendix I. 2. See text page 9 regarding thyratron grid control.

TABLE IV

MAXIMUM POWER THAT COULD BE CARRIED OVER TEST LINE PRIOR TO TRIPPING NORTH LINE, WITHOUT LOSS OF SYNCHRONISM

Test no.	Line kv.		Estimated maximum power in kv.		Excitation
	Martin Dam	Atlanta	From test	Corrected to 110 line kv.	
5	114.0	102.0	36,000	37,500	Form Y—Standard Exciter
6	113.5	102.0	36,000	37,600	Form K—24 Exciter
7	114.0	104.0	36,000	36,700	Hand control
20	112.0	105.0	36,000	37,000	Form Y—250 V/sec.[1]
23	110.0	102.0	35,000	37,600	Form Y—500 V/sec.[1]

1. See text page 9 regarding thyratron grid control.

closer than the probable error in the test readings. Fig. 10 shows a comparison of calculated and test results during a line-to-ground short circuit. Figs. 11 and 12 present a comparison of calculated and test results when power over the test line is suddenly increased by tripping the north line.

VI. Notes on Test Results

It should be borne in mind that the results herein presented were obtained on commercial power systems under actual conditions of operation, and mostly during times of peak load. This very fact precluded the attainment of results of an accuracy approaching laboratory precision. Every test was accompanied by a severe disturbance on the system, and it was therefore deemed desirable not to try to check any points unless for some reason the test had been a failure. There was no checking merely for the sake of checking. In some of the tests, the tripping of certain switches or the manipulation of load was necessarily in the hands of persons remote from the scene of test and carried out on telephone instructions. This condition did not increase the probability of satisfactory results.

The test was carried out and the power measurements made at the input end of the test line. Practically all calculations made heretofore on the power limit of a line have considered the maximum amount of power obtainable at the receiver end. The relationship between these two is presented in Fig. 13. Curve *C* in this figure indicates the maximum power which could be obtained if the reactance of all terminal apparatus at both generator and load could be reduced to zero. It will be noted that the maximum power at the generator end occurs slightly after the systems have started to fall out of step and is somewhat greater than when the receiver is at a maximum. The absence of second harmonic in these curves is owing to the method of calculation, and does not detract from their value for comparative purposes.

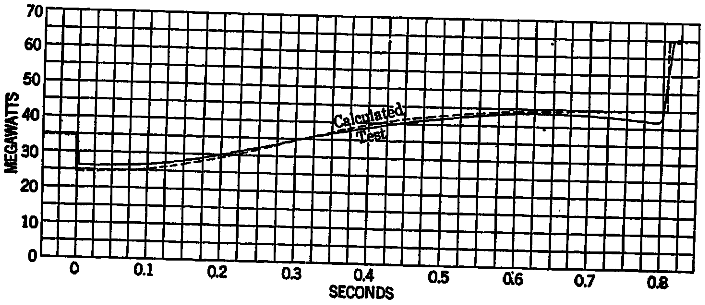

Fig. 10—Test No. 25A. Comparison of Calculated and Test Values of Instantaneous Power during Line-to-Neutral Short Circuit on Martin Dam High-Tension Bus

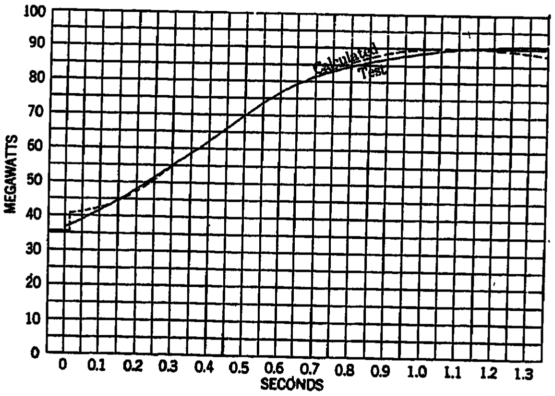

Fig. 11—Test No. 7B. Comparison of Test and Calculated Values of Instantaneous Power during Sudden Increase in Load by Tripping North Line

In certain of the tables, reference is made to control of the Martin Dam generators by types *W* and *Y* regulators. The type *W* regulator is that described by Messrs. R. E. Doherty,[3] C. A. Nickle, and R. M. Carothers[4] in papers presented at the St. Louis regional meeting of the Institute in March 1928. The type *Y* is the commercial form thereof also referred to in those papers.

Some of the tests were made with the exciter fields supplied from a thyratron. The grid control for the thyratron was from d-c. batteries. Such control does not produce an exciter voltage decay at the same rate as the voltage rise. From the standpoint of aiding the new type of regulator to provide positive damping for the system to smooth out oscillations as rapidly as possible, it appears that the rate of decrease of exciter voltage should be approximately equal to the rate of increase. For this reason, the new regulators probably could not show their maximum efficiencies.

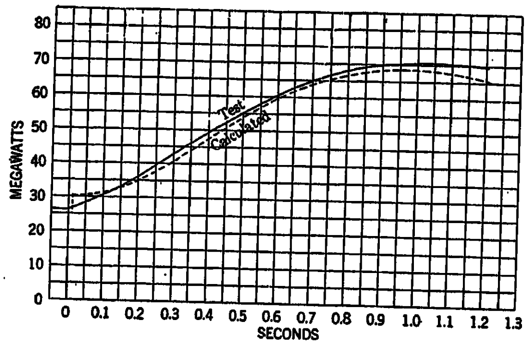

Fig. 12—Test No. 7A. Comparison of Test and Calculated Values of Instantaneous Power During Sudden Increase in Load by Tripping North Line

Before starting the tests, the maximum power which could be transmitted over the test line to the Georgia system under steady conditions was calculated. The calculation was based necessarily upon assumptions with regard to the reactance of the Georgia System and the values of voltage at each end of the test line

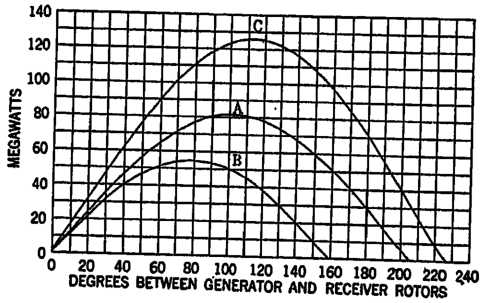

Fig. 13—Calculated Power Angle Curves for Test Line and Systems under Conditions of Test No. 10

Curve *A* Power at generator end of line under test conditions. The maximum of this curve is the value observed on all these tests

Curve *B* Power at load end of line under test conditions

Curve *C* Power at generator end of line if the power were limited only y the impedance of the test line

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3. July Quarterly Trans., p. 944.
4. July Quarterly Trans., p. 957.

which could be used under the test conditions of abnormal loading of the south line. Data from which to make such assumptions were meager, and the preliminary estimates of maximum power were too low. In the tests, it was possible to carry with fixed excitation amounts of power nearer the maximum theoretical limit than had been anticipated. The margin left for improvement owing to the different excitation systems proved to be considerably less than expected. Considering this, and the unfavorable condition as regards thyratron grid control, as well as the possible errors in the test results owing to the conditions under which they were made, no conclusive data were obtained on the efficiency of the new regulator, or of high-speed excitation.

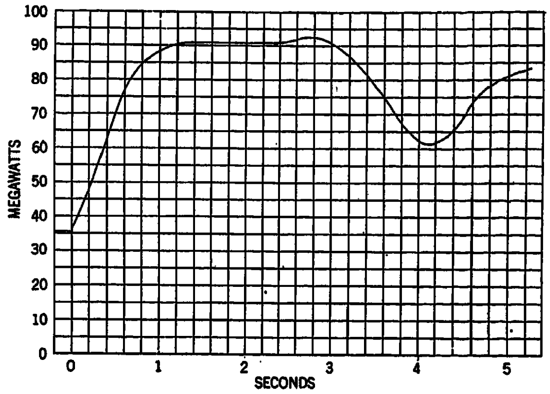

FIG. 14—FLAT TOPPED POWER WAVE ON FIRST SWING

Plotted from data obtained on test 5A

An examination of the wattmeter oscillograms of tests in which the two systems were set to swinging with respect to each other, but not pulled out of synchronism, shows that the Alabama system as a whole, with respect to the Georgia system, swings at a periodicity of approximately two seconds, (Fig. 4). When the two systems are set into oscillation as the result of tripping the north line, there appears to be a fair degree of damping; but when the oscillation results from a short circuit, the damping between the two systems is negligible. When Martin Dam alone is connected to the test line, it swings, with respect to the Georgia system, with a periodicity of about ¾ sec. and there is very little damping, (Fig. 6). Fig. 8 shows that the Martin Dam swings with respect to the Alabama system with a periodicity of about ⅝ sec. with practically no damping. From the foregoing, it is evident that when, by sudden increase in load, the Alabama and Georgia systems were made to oscillate with respect to each other, there was an appreciable amount of damping, but very little of it is located in the Martin Dam station.

The exact reasons for the marked difference in the degree of damping out of oscillations between the two systems, when caused by short circuits, and when caused by sudden increases in load, form an interesting and profitable field for future study.

There was a certain amount of variation in the power over the test line, even at relatively light loads. This was owing to the tendency of the two systems to drift in speed with respect to each other. This variation, however, increased the difficulty of obtaining the desired degree of precision when making some of the tests. In the short-circuit tests and those when the north line was tripped, sometimes a test would be obtained which was considered to be very near the top limit. Then it would be attempted to try the next test with the power increased by approximately 2000 or 3000 kw. However, with the power over the test line varying by 5000 kw., in a somewhat irregular manner, the next test might turn out to be the same as the last, or it might show an increase of 5000 to 7000 kw. Owing to the undesirability of subjecting the systems to a large number of severe disturbances, it was not deemed desirable to try for too close a check of these points.

In looking at the oscillograms of some of the short-circuit tests and of those when the north line was tripped, it will be noted that on the first swing the power rose to a maximum value, the duration of which was considerable compared to the periodicity of the subsequent swings. The significance of these flat-topped waves on the first swing may best be explained by a mechanical analogy. A well balanced bicycle wheel, when raised from the ground, will come to rest with the air valve at the bottom. When the air valve is moved a certain amount, the wheel will oscillate like a pendulum with a periodicity which is practically independent of the amplitude. However, if the wheel is given enough of an impulse to carry the air valve almost, but not quite, past center at the top, it will hesitate in this position for a considerable period. This hesitation at the maximum of the first swing is analogous to the flat-topped power wave observed on these tests. The existence of the flat-topped wave indicates that the systems were near to losing synchronism. The greater the duration of this first swing maximum the nearer they were to going out of step. This phenomenon provides a method for estimating the true

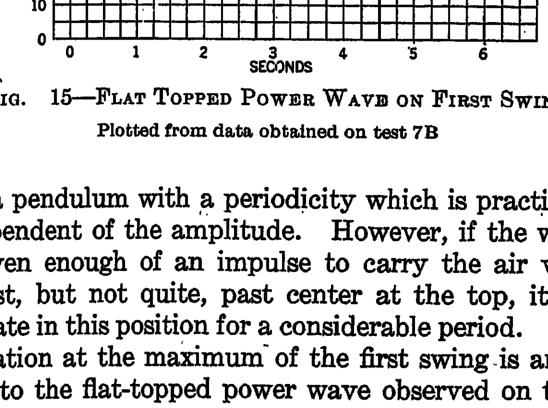

FIG. 15—FLAT TOPPED POWER WAVE ON FIRST SWING

Plotted from data obtained on test 7B

value of maximum power under certain test conditions when the two values actually obtained were so far separated as to leave some uncertainty as to what the maximum value actually was. The results presented in Tables III and IV are the maximum values of power estimated from the test results by examining the characteristics of the power waves and also by examining the nature of the decrement in the voltage waves. Figs. 14 and 15 have been derived directly from the test data to show more clearly this flat-topped wave on the first swing.

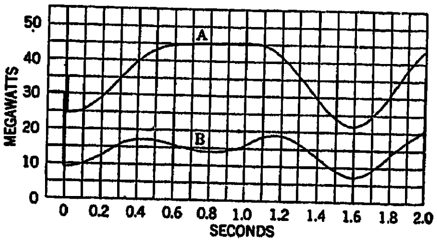

Fig. 16—Flat-Topped Power Wave on First Swing Occasioned by Line-to-Neutral Short Circuit Calculated for Conditions Observed on Test 25A

Curve *A* Generator power
Curve *B* Receiver power

To check the theory as to the cause of these flat-topped waves, calculations were made to see if they could be produced mathematically. A condition was assumed in which the swing was started by a short circuit; but the phenomenon should be the same whatever the cause. Fig. 16 is the result. In studying Fig. 16, Figs. 17 and 18 should also be noted. They show the relation between angle time and angle power, calculated for the same phenomenon. It is interesting to note from these curves that it is possible for the angle between load and generator to exceed the critical steady-state angle by a considerable amount without losing synchronism.

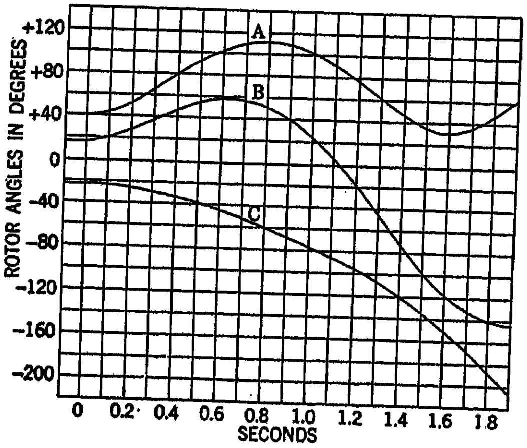

Fig. 17—Angle Time Curves Calculated for Same Conditions as Fig. 16

Curve *A* Total angle between generator and receiver rotors
Curve *B* Absolute angle of generator rotor
Curve *C* Absolute angle of receiver rotor

While making these tests, it was felt desirable to obtain some check on the expectation that a reduced duration of short circuit would be beneficial to stability. Tests were made, therefore, with the short circuit maintained for differing times, and the results are shown graphically in Fig. 19. It should be remembered that these data show the result with a metallic short circuit from one phase-to-ground directly on the 110-kv. bus at Martin Dam. No tests were taken with any other form of short circuit. It is expected that similar results would be obtained if it had been possible to try shorts with varying amounts of resistance and reactance simulating conditions when a fault occurs at some

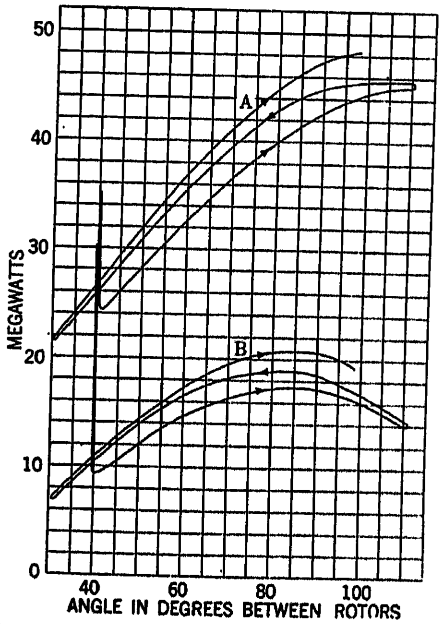

Fig. 18—Power Angle Curves Calculated for Same Conditions as Fig. 16

Curve *A* Generator power
Curve *B* Receiver power

Note that the Martin Dam generators and the load swing apart by over 110 deg. without losing synchronism

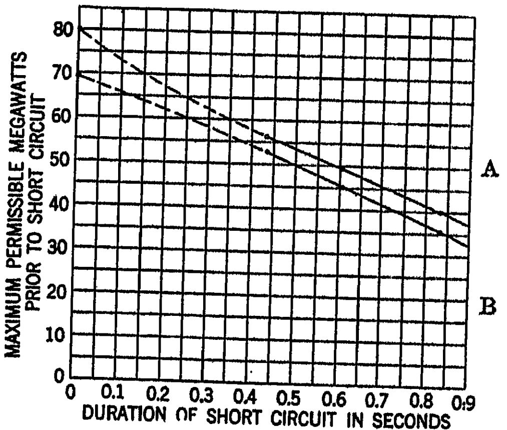

Fig. 19—Relation between Duration of Line-to-Neutral Short Circuit and Maximum Power That Can be Carried Prior to Short Circuit Without Losing Synchronism

Curve *A*—High speed excitation
Curve *B*—Constant slip ring volts

distance from the station, but they would not necessarily be comparable in magnitude.

Owing to the high total resistance of the test circuit, it is to be noted that when operating at values near the pull-out a very substantial part of the input to the test line was consumed in line losses. During the tests in which the north line was tripped throwing the total load on the test line, the total line losses were increased by some 15,000 kw. This is shown in Fig. 13. Thus additional load was created which tended to slow down both systems. Owing to the difference in the power-frequency and load-frequency characteristics of of the two systems, this increased load undoubtedly had some effect on the test line loading.

In the tests for maximum power under no-disturbance conditions, after passing the maximum value at the receiver end, the generator load continues to increase owing to greatly increased line losses. At this time, apparatus at both ends of the line tend to slow down in absolute speed, thus keeping in "near" synchronism for quite a period. Thus, the process of pulling out of step is one requiring considerable time, probably of 15 to 30 sec. duration, possibly even longer.

VII. Conclusions and Summary

The safe loading of the test line for operating conditions, considering that the north line may be tripped at any moment as a result of a disturbance on it, appears to be about 35,000 kw. From the standpoint of maintaining synchronism during short circuits on other circuits, the safe loading of the test line depends on the duration of the short circuit, and for a one-second duration, appears to be about 35,000 kw.

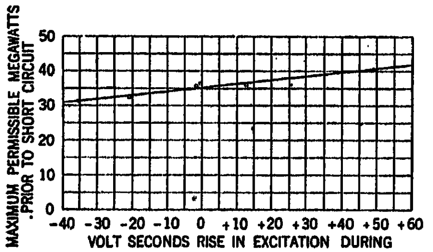

Fig. 20—Relation between Excitation and Maximum Power that can be Carried Prior to Line-to-Neutral Short Circuit of 0.83 Sec. Duration without Losing Synchronism

The gain in power which could be carried with the increased speeds of excitation used in these tests appears to be not great. Further consideration is given to the effect of excitation speeds in Appendix I, contributed by F. R. Longley, who has made most of the mathematical computations in connection with working up the short-circuit tests and those when the north line was tripped.

The use of a voltage regulator showed some gain in steady-state power limit over the value with fixed excitation. For reasons already noted in the text, the tests were not conclusive with reference to the efficacy of the new regulators.

While the Alabama and the Georgia systems showed a fair degree of damping when made to oscillate with respect to each other by load increases, there was very little damping evidenced when the oscillation was between Martin Dam and either of the two systems. This would indicate the desirability of providing waterwheel-driven generators with amortisseur windings.

A reduction in the duration of short circuits appears to have a very beneficial effect upon the amount of power which can be carried during a short circuit.

Information was secured concerning the equivalent reactance,[5] damping, and inertia of the systems on which the tests were made, which permit very close mathematical checks on the results attained.

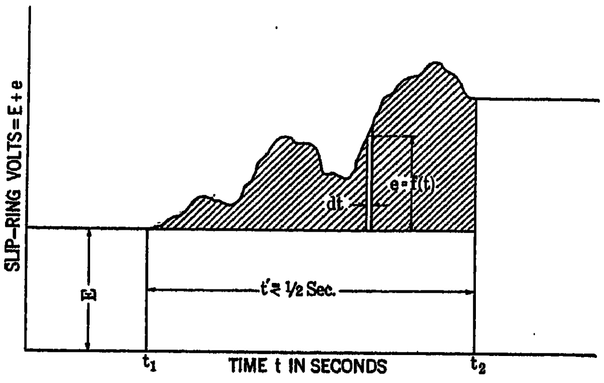

Fig. 21

The authors desire to express their appreciation of the assistance rendered by the executives of the companies concerned, in granting permission to make the tests; to the operators, load despatchers, maintenance crews, and engineers of the operating companies for wholehearted cooperation in carrying out the tests; and to members of the Engineering Department of the General Electric Company for valuable assistance in working up the data, and for many pertinent suggestions as to methods of analysis and interpretation.

Appendix I

The Effect of Excitation Upon the Maximum Power that can be Carried Through a Transient Disturbance

By F. R. Longley[6]
Associate, A. I. E. E.

An excitation system may be defined as an arrangement to control flux linkages of synchronous apparatus in some predetermined manner. The efficiency of the system depends upon its ability to produce the proper change in flux linkages the moment the change is required.

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[5] By "equivalent reactance" is meant that value of reactance which, for purposes of calculation, is used for the actual reactance of a large composite system.

[6] Electrical Engineer, General Electric Co., Schenectady, N. Y.

In most of the previous papers on high-speed excitation, consideration has been given only to the rate of rise of exciter voltage; that is, volts per second, or, in some cases, the maximum, or ceiling voltage, as a measure of the efficacy of the system.

To effect a change in flux linkages requires time. Neither volts per second nor ceiling volts alone will produce the change. They must have time in which to operate in order to overcome the self inductance of the field circuit and produce the required change in flux.

It will be noted that the excitation versus power curve in Fig. 20 is plotted in terms of a new unit; namely, volt-seconds rise in excitation. As explained below, this unit, with respect to time, is the integral of the excitation voltage-rise. Under normal, steady conditions, the excitation of an alternator is measured in volts, but under the usual transient conditions the effect of the excitation system would be more logically expressed by the new unit volt-seconds. Under steady conditions, a change in volts will produce a proportionate change in flux, while under transient conditions, only a change in volt-seconds will produce a change in flux. This relation is clarified in the following discussion:

Mr. R. H. Park has called attention to the following simple relationship existing between excitation volts, time, and the flux linkages of the field circuit of large alternators when the time considered is equal to or less than half a second: The *change* in flux linkages will be approximately equal to the *change* in volt-seconds; that is, to the *increase* in the area under the volt—time curve. The mathematical demonstration of this statement is given below.

The increase in volt-seconds for the time $t' \lesseqgtr \frac{1}{2}$ second is the shaded area illustrated in Fig. 21. During the time t' the rise in flux linkages will be approximately proportional to this area.

The rise e in slip-ring volts will have the relation

$$e = L \frac{di}{dt} + i R$$

where

i = rise in field current produced by e.
t = time.
L = inductance of field circuit.
R = resistance of field circuit.

For the short time considered, $i R$ is small when compared to $L \frac{di}{dt}$ and may be neglected. Then

$$e \cong L \frac{di}{dt}$$

$$i \cong \frac{1}{L} \int_{t_1}^{t_2} e\, dt$$

The increase in field current i will be proportional to the increase in field flux ϕ or

$i = k \phi$

where k is a constant, and

$$\phi \cong \frac{1}{k L} \int_{t_1}^{t_2} e\, dt$$

The integral expression $\int_{t_1}^{t_2} e\, dt$ is the shaded area in Fig. 21 and the rise in field flux ϕ is, therefore, approximately proportional to the rise in volt-seconds. The change in volt-seconds is absolutely independent of the shape of the slip-ring volts versus time curve, and at the end of the time, t', the change in flux linkages of the alternator field circuit depends only upon the magnitude of the integrated area, shown shaded in Fig. 21 of change in excitation volts versus time.

Load-Time Curves of Synchronous Condenser rated ATI-12-30,000 M-600 S-13,800 Volts when connected to an infinite bus and the following excitations applied when the machine is carrying 10,000 leading kv-a. (0.05 seconds allowed for regulator to operate.)

Curve Number	Rate of Voltage Rise	Ceiling Voltage
1	∞	784
2	6400	900
3	5000	953
4	4000	1041
5	3200	∞

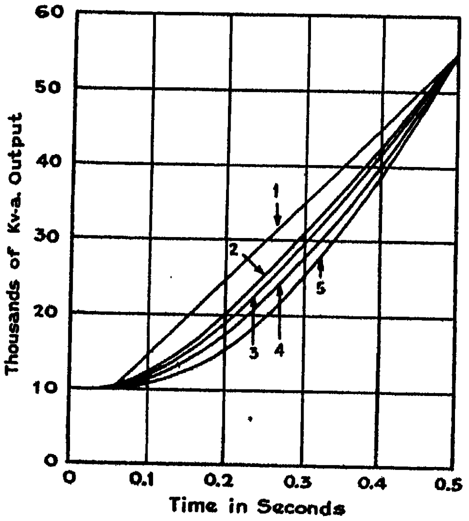

Fig. 22

As a proof that the increased $i R$ drop produced in the field circuit of large alternators, by increasing the slip-ring voltage, is negligible under the conditions described, Fig. 22 is presented.[7] For each of the five curves the applied increase in volt seconds was the same at 0.5 seconds although the rates of excitation voltage rise, and the maximum or ceiling excitation voltages, varied from 3200 volts per second to infinite volts per second, and from 784 volts ceiling to infinite volts ceiling. It will be seen that all the curves have the same ordinate at the instant when the volt seconds are the same, namely, 0.5 seconds. The condenser was assumed connected to an infinite bus and its rise in kv-a. would be proportional to its rise in flux. The curves in Fig. 22 were calculated, but curves of this type can be, and have been, checked by test with an exceedingly small error.

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[7] Fig. 22 appeared as Fig. 3 in *Super-excitation of Synchronous Condensers*, by D. M. Jones, presented at the Regional Meeting of the A. I. E. E., District No. 2, Baltimore, Md., April 17-20, 1928.

After the excitation voltage reaches its ceiling, it becomes constant and the rise in flux linkages of the alternator field circuit will thereafter be an ordinary exponential curve.

During transient disturbances, it is desirable to limit the maximum swing of the alternator rotor. This may be done by increasing the air-gap flux during the first half swing of the rotor, and therefore, by increasing the slip-ring volt seconds. If a certain number of volt-seconds is available during the first half swing it is best to apply them as quickly as possible.

From the above discussion, it is clear that in designing an excitation system of such characteristics as to be most effective in limiting the first swing by increasing flux linkages, two factors are paramount in importance. First, the maximum voltage applied to the slip-rings must be as high as permissible from other considerations; second, that maximum voltage must be attained as promptly as possible, commensurate with other design limitations. This in order to get to that maximum voltage as early as possible during the first swing, calls for an exciter capable of applying a relatively high voltage to the slip-rings, and also capable of an extremely high rate of voltage rise; that is, an exciter capable of producing the maximum change in volt-seconds.

In each of the tests described in this paper, the rise in volt-seconds was applied in a similar manner. The slip-ring volts started from a minimum and rose uniformly to a maximum. The change in volt-seconds should therefore provide a means of comparing the efficiency of the excitation systems in limiting the maximum rotor swings.

The duration of the short circuit for seven of the Martin Dam tests was so nearly the same, that an average value of duration could be used for each test with very little error.

The rate of excitation rise for each of the seven tests was different, and therefore permitted a direct comparison between the rise in volt-seconds and the maximum permissible power that could be carried prior to the short circuit without loss of synchronism. This relation is shown in Fig. 20. The negative volt-seconds are a result of the drop in slip-ring volts when the alternator field current increased during the short circuit.

The foregoing touches only a small part of a subject which has many other aspects. A more comprehensive treatment will be made in a paper to be presented before the Institute at a futuer date.

Discussion

A. Dovjikov: The studies which Messrs. Jones and Treat have been making on the system of the Southeastern Power and Light Company are extremely interesting as they provide data on power limits of actual systems under operating conditions rather than miniature laboratory conditions.

We note from the discussion under "Curves and Tables of Results" that the authors found that oscillographic wattmeters having any appreciable inertia were not accurate when the power was varying rapidly and that instantaneous type instruments were used for checking. The tests point out the care with which all metering equipment must be selected, having in mind its appropriateness for the conditions under which the measurements are made. Our experience was similar and led to the development of single- and two-phase instantaneous and three-phase average oscillographic wattmeters which are now available and are free from defects mentioned in the paper.

Referring to the conclusions reached by the authors, I believe that the statement that "the gain in power which could be carried with increased speed of excitation used in these tests appears to be not great," is at least too pessimistic. If my understanding of Fig. 20 is correct it appears as though a gain of 28 per cent in power limit was obtained by speeding up the excitation. This amount, of course, would be quite worth while.

Their conclusion relative to the recommendation of providing water-wheel-driven generators with amortisseur windings appears to be based on insufficient evidence. Several considerations, into which I have not sufficient time to go, make us believe that from the point of view of stability it would be better to omit damper windings, especially of the low-resistance type that have been previously recommended, from water-wheel-driven generators. In general, the studies which my associates have made relative to this subject indicate the undesirability of damper windings for water-wheel-driven generators except when their use is required by other considerations, as for example in connection with automatic operation.

F. R. Longley: Comparison of the three-phase and single-phase wattmeter oscillographs: The accompanying curves (Fig. 1, herewith) of the transient power during a single-phase line-to-ground short circuit show how closely the three-phase wattmeter oscillograph element and the three single-phase wattmeter oscillograph elements check, when the curve of the three-phase element has been corrected for the effect of its inertia.

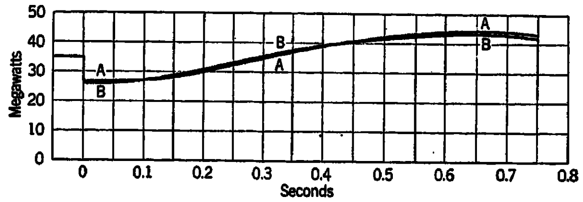

Fig. 1—Test Values of Instantaneous Power during Line-to-Neutral Short Circuit on Martin Dam High-Tension Bus

Curve *A*—Power from three-phase single-element oscillograph
Curve *B*—Power from single-phase three-element oscillograph

Curve *A* was obtained from the film of the three-phase wattmeter after a few hours work. It required a week to obtain curve *B* from the terribly distorted film curves of the single-phase elements

The effect of excitation upon the maximum power that can be transmitted through a transient disturbance: It should not be assumed that the total rise in power shown in Fig. 20 can be obtained by ordinary high-speed excitation.

Reference to Table III will show that the maximum gain in volt-seconds during the first half swing of the generator was 49.3 obtained during test No. 25, with a rise in exciter potential of 500 volts per second.

From Fig. 20, the maximum power with zero volt-seconds (constant slip-ring volts) is 35,000 kw. With 49.3 volt-seconds the maximum power becomes 41,000 kw. The gain is 6000 kw. or 17 per cent. All other tests show a smaller percentage gain.

The negative volt-seconds in Fig. 20 were produced by leaving a part of the resistance of the alternator field rheostat in the alternator field circuit between the exciter and the slip rings. The rise in field current during the short circuit produced an increase in the resistance drop between the exciter and the slip rings with a consequent reduction in the slip-ring volts. Any negative volt-seconds reduced the maximum power in the same manner that positive volt-seconds increased it. It must be remembered, however, that 100 per cent maximum power is that obtained with zero volt-seconds.

Robert Treat: The paper states that not entirely satisfactory results were secured in measuring power changes in the current when such changes were sudden. I think, however, that they are as reliable as many other parts of the test, for the reason that entire reliance in drawing conclusions was not placed in one oscillographic method of recording power. Checks were also made with indicating and recording instruments at both ends of the line. In addition to the one type of oscillograph which contained some inertia and which therefore, as stated in the paper, did not faithfully follow sudden changes in power, check oscillograms were also made with the type which records single-phase power. In finally working up the tests, fairly substantial agreement was obtained from all the methods.

When we came to work up the results, it was found that the single-phase wattmeter oscillograph, although it was substantially instantaneous and therefore free from the difficulties of the other instrument, recorded so faithfully the power in the circuit that it became difficult to interpret even those results because the power itself was no longer sinusoidal. On short circuits it contained harmonics and the correct value of power could not be obtained directly and readily from these oscillograms. It was necessary to magnify the graphs and integrate the areas to find the true power. In the end, however, a fairly substantial agreement was obtained.

It should be noted that a portion of the gain in power mentioned by Mr. Dovjikov was obtained simply in going from hand control to regulator control, and not all of it by increasing the speed of the exciter. As near as could be estimated from the test results, half of the total gain was attributable to control of the exciter voltage by regulator; that is, the control of the voltage of the exciter as installed. It is a particularly low-speed, sluggish exciter. Mr. Dovjikov questions our conclusion that amortisseur windings would be helpful to stability. I agree with him that it is not a simple phenomenon, but it would have been interesting if he had presented some substantiation of his opinion. Of course we were unable to make tests on the Martin Dam generators with and without amortisseur windings, so our conclusion of their value is inferred rather than proved. Nevertheless, when the test machines were set into violent oscillation with respect to the system, there was very little tendency toward damping, and the conclusion seems entirely reasonable that properly designed amortisseur windings would have been beneficial. This conclusion is supported by analytical work done both in connection with these tests, and for other studies.

So far as I am aware, this is the first time that tests of exactly this nature have been made on a power system. A high devotion to anything tending to advance the art, to permit them to improve their service, must have motivated the executives of the power companies concerned in embarking upon tests of this sort. It is a rather high tribute to the effectiveness of the operating personnel that service was not impaired in the least.

Some Photoelectric and Glow-Discharge Devices
and their Applications to Industry

BY J. V. BREISKY[1] and E. O. ERICKSON[1]
Associate, A. I. E. E. Associate, A. I. E. E.

Synopsis.—During the past few years, intensive research work has been carried out on some photoelectric and glow-discharge devices. More recently, certain applications of these devices to the industry have been undertaken. This paper presents some of the results attained.

* * * * *

Introduction

UNTIL very recently, applications of vacuum and gas filled devices in industry have been comparatively limited except for the familiar electric lamp, the X-ray tube, and the vacuum tube for radio receiving and broadcasting and for communication circuits. Thus far, industry has made very little use of photoelectric and glow-discharge devices, this delay in making widespread use of such devices being due no doubt to the fact that until recently they had not been sufficiently developed for applications where reliability, long life, and constancy are required. Conditions are changing rapidly, however, and as development work progresses, the applications of these devices will become more and more widespread.

Photoelectric devices have been used in laboratories for some time, and are now an essential feature in television, telephotography, radio-photography, and talking motion pictures. The photoelectric cell can solve many industrial problems, for this light-sensitive device, unlike the human eye, is unhampered by the tricks of human psychology and fatigue. Some glow-discharge devices operate on as little as a few millionths of a watt, and have an amplification factor of several millions. The possibilities of such sensitive apparatus must be apparent.

A number of new developments on photoelectric and glow-discharge devices have been pursued during the last two or three years and some of these have been completed, while others are still in the development stage.

It is the purpose of this article not only to describe some of these recently developed or recently improved devices,—such as photoelectric cells, selenium cells, photo-glow tubes, and grid-glow tubes,—but also to point out their fields of application and to describe several of the specific applications that have been undertaken, or are under way at present; as, for example, smoke recorders, fire and flash detectors, apparatus for the sorting of materials, paper-machine control, oilburner safety devices, etc.

Theory and Description of Devices

General. While differing in construction and in application, the devices discussed in this paper in reality have much in common. The extent to which these devices are related can be seen from the following general considerations.

1. *Conductivity in High Vacuum.* When sealed in a glass tube which is highly evacuated, two electrodes, such as A and B in Fig. 1a, would be perfectly insulated from each other for normal voltages, assuming no leakage took place over the surface of the glass.

If, however, one of the electrodes as A were to be heated to incandescence or illuminated with light of suitable frequency the inter-electrode space would, upon application of a positive potential to electrode B, be found to be a relatively good conductor of electricity. In either case, if current be plotted as a function of applied voltage, a curve similar to that shown in Fig. 1B would be obtained. This curve is a fundamental one applying to the case of the conductivity of a high vacuum space between two electrodes, one of which is source of electrons.

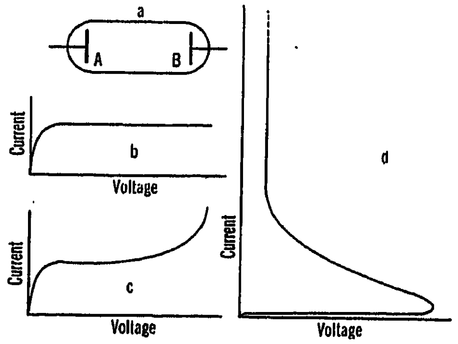

Fig. 1—(a) Elementary Vacuum or Gas-Filled Tube
(b) Current—Voltage Curve for Vacuum Device with One Active Electrode
(c) Current—Voltage Curve for Gas Filled Device with or without an Active Electrode
(d) Continuation of Curve (c)

As will be shown later, the high vacuum photoelectric cell displays the general characteristic presented in Fig. 1b.

2. *Conductivity of a Gassy Space.* If the space

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[1] Supply Engg. Dept., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

Presented at the Regional Meeting of the Southern District of the A. I. E. E., Atlanta, Ga., Oct. 29-31, 1928.

between the two electrodes in Fig. 1a be gas filled, upon applying a voltage it will be found that the electrodes are no longer as nearly perfectly insulated from each other as they were when the space was highly evacuated, even though no purposely applied ionizing agent be allowed to act on the gas. The space will also be found to conduct equally well in either direction.

The conductivity is attributed to spontaneous ionization; that is, a form of ionization not due to ordinary ionizing agents but rather to the so-called Ultra Gamma Rays or Cosmic X-rays, also known as "penetrating raditions." By these means, the neutral gas molecules are ionized or broken up into positive and negative ions, which under the influence of the applied voltage migrate respectively towards the negative and positive electrodes. This migration of ions constitutes a flow of current so small in magnitude as to require the most sensitive instruments to detect its passage. By plotting current as a function of voltage, a curve as shown in Fig. 1c can be obtained, differing from that shown in Fig. 1b in that a rising characteristic is obtained for the higher voltages. This increase in the current over and above what is accounted for by the ionizing agents previously mentioned occurs for voltages which are sufficient to give to the migrating ions sufficient velocity to ionize the neutral gas molecules upon colliding with them. The newly formed ions resulting take part in the migration to the respective electrodes, and by so doing result in the higher current values observed.

By a continued increase in voltage, a point is reached at which the current becomes self-sustaining and independent of the primary ionizing agent. If suitable resistors, sufficiently high in value, be connected in series with the tube and if the applied voltage be increased, a curve between current and inter-electrode voltage similar to Fig. 1d can be obtained,[2] where the most extreme voltage recorded is the one at which the current becomes self-sustaining. It will be recognized that the initial portion of curve *d* is the same as curve *c* drawn on a different scale. Over a considerable portion of the curve *d* in the region immediately above and following the sharp knee in the curve, the currents as obtained in the above mentioned observations are oscillatory in nature ranging in frequency from only a few pulsations per second at low voltages to frequencies above the audible range for the higher total circuit voltages. These same currents have further significance, in that they represent the "threshold" values of current. For each particular voltage there is a definite "threshold" or minimum value of current which must be supplied to the discharge before it is capable of progressing to that form of discharge characterized by the constant voltage drop portion of the curve. The manner in which currents and voltages are related is depicted by that portion of the curve *d* under discussion. It is the phenomenon as depicted in and applying to Fig. 1d which accounts for the action of the grid-glow tube.

If the space in Fig. 1a be gas filled as before, and if one of the electrodes were to serve as a source of electrons in itself, being either heated to incandescence or illuminated by light of suitable frequency, the device would have the same characteristics as depicted in curves *c* and *d*. In this case the effect of the penetrating radiations can be neglected, as the one active electron emitting electrode will normally serve as a source of a much greater number of ions than the penetrating radiations could account for. Neglecting the effect of the penetrating radiations, the device will exhibit a unidirectional conductivity, permitting the flow of current only when the inactive electrode is positive with respect to the electron emitting electrode. The gas-filled photoelectric cell having a single photoelectrically active electrode operates over a characteristic essentially that as shown in curve *c*.

Keeping in mind the significance of the threshold currents as brought out in a previous paragraph, and also the action of a device having a single electron emitting electrode as described above, it can be seen that this electron emitting electrode can be made to function as a controllable source of supply of threshold currents. Accordingly, with proper design, the device mentioned in the last paragraph above can be made to operate over the extended part of its characteristic as presented in curve *d*. The photo glow tube is a device which has this characteristic.

If a pulsating glow-discharge be established with an alternating voltage impressed across two initially inactive electrodes in a device similar to that shown in Fig. 1a, the currents which flow in opposite directions will be the same provided the two electrodes are equal in area. If, however, one of the electrodes is reduced in area, rectification will be obtained. The degree of rectification obtained will depend upon the relative areas of the two electrodes. The current which passes in any one direction is roughly proportional to the area of the electrode which, at the instant, is functioning as a cathode.

The application of glow-discharge devices to the general problem of rectification has not been made the subject of any part of this paper.

The following table will serve to show the relation between the various photoelectric and glow-discharge devices in agreement with the general discussion above.

TABLE I

	High vacuum	Gas space
Electrodes Inactive....		Two electrode glow tube Grid-glow tube
One active Electrode..	High vacuum Photo cell	Photo-glow tube Gas-filled photo cell

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[2] "On the Sparking Potentials of Glow-Discharge Tubes," James Taylor, *Phil. Mag.*, 269.3, Ser. 7, Feb. 1927.

Light Sensitive Devices

1. Photoelectric Cell. The first observation of the photoelectric phenomenon was made in 1887 by Hertz, who noticed that a spark would pass across a spark-gap more readily when the electrodes were illuminated than when they were in darkness. A year later Hallwachs noted (a) that a negatively charged body readily loses its charge and (b) that an initially uncharged body acquires a positive charge when illuminated by ultraviolet light. In 1889 Elster and Geitel showed that the more electro-positive metals, such as rubidium, potassium, sodium, etc., would display this same effect when exposed to ordinary light of the visible spectrum. The effects are due to the emission of negative electrons by the photoelectrically active material, which emission takes place when that material is illuminated by light of suitable frequency.

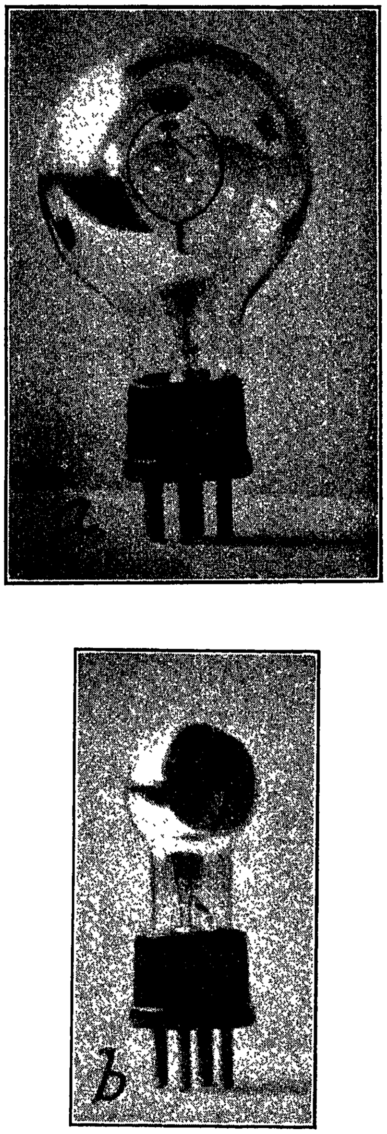

Fig. 2—Photoelectric Cells Showing Type of Base Mounting. The Two Sizes are Respectively (a) 2½ In. and (b) 1¼ In. in Diameter

The modern photoelectric cell modeled somewhat after the originals by Elster and Geitel takes advantage of this action and reduces the phenomenon to one having extremely practical uses.

Two such cells as developed by Dr. Zworykin of the Westinghouse Research Laboratories are shown in Fig. 2. The spherical portions of the large and the small size cell in parts *a* and *b* of Fig. 2 are respectively 2½ in. and 1¼ in. in diameter, both sizes being mounted in standard tube bases for ease in mounting and in making connections.

Both sizes are made in the high-vacuum and gas-filled types. The particular characteristics of each type will be pointed out in a later paragraph.

The larger cell is shown in greater detail in Fig. 3. The photoelectrically active cathode consists of a layer of photo active alloy deposited on the inner surface of the spherical portion of the cell. A cleared circular aperture serves as a window for admitting light to the active surface. A short wire lead makes connection through the glass press between the active layer and one prong on the base.

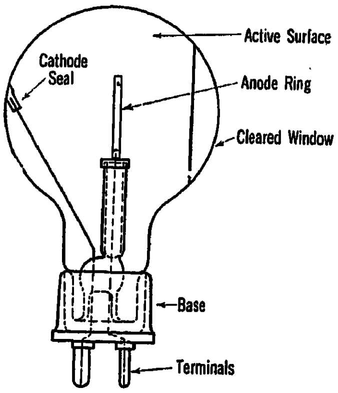

Fig. 3—Details of the 2½ In. Diameter Photoelectric Cell Showing Interior Structure

The anode structure consists of a ring of metal ribbon supported in the center of the cell by a section of wire which passes through the press and out to a second prong on the base. Means are provided to insure freedom from internal stray leakage currents.

A typical curve of cell response plotted as current in microamperes per lumen of light flux at various voltages for a particular high-vacuum cell is shown in Fig. 4a. Curve 1 of Fig. 4b shows the relation between the same quantities for a particular gas-filled cell. The two types of cells display the typical curves which were presented in parts *b* and *c* of Fig. 1 as applying to high-vacuum and gas-filled devices having an electron emitting electrode.

The high-vacuum cell is seen to yield its saturation value of current at a comparatively low voltage. The gas filled cell while displaying a similar behavior at the lower voltages shows a rising characteristic on the higher voltage due to the additional conductivity resulting from the ionization of the gas. Curve 2 of Fig. 4b is the illumination limit curve applying to the same gas filled cell. Its significance lies in the fact that at any particular voltage, as for example V, at which time the cell passes i microamperes per lumen, the maximum amount of light flux which can be supplied to the cell without causing the cell to glow is represented by L lumens. This illumination limit curve is essentially the "threshold" current portion of the curve previously discussed and presented in part d of Fig. 1. If for any particular application it is considered desirable to take advantage of the extreme sensitivity which the cell has at the higher voltages, it can be seen from this curve that the luminous flux must be reduced. For the particular cell whose characteristics are presented in Fig. 4B, it is accordingly evident that if for example it is desired to operate at a sensitivity of 30 microamperes per lumen the maximum luminous light flux supplied to the cell must be held close to, but not above 0.102 lumens. It is to be pointed out that Curve 2 represents the limiting conditions, which in actual operation are purposely avoided by a safe working margin. Obviously the high-vacuum photo cell, by reason of its tendency towards saturation, is not subject to these limitations.

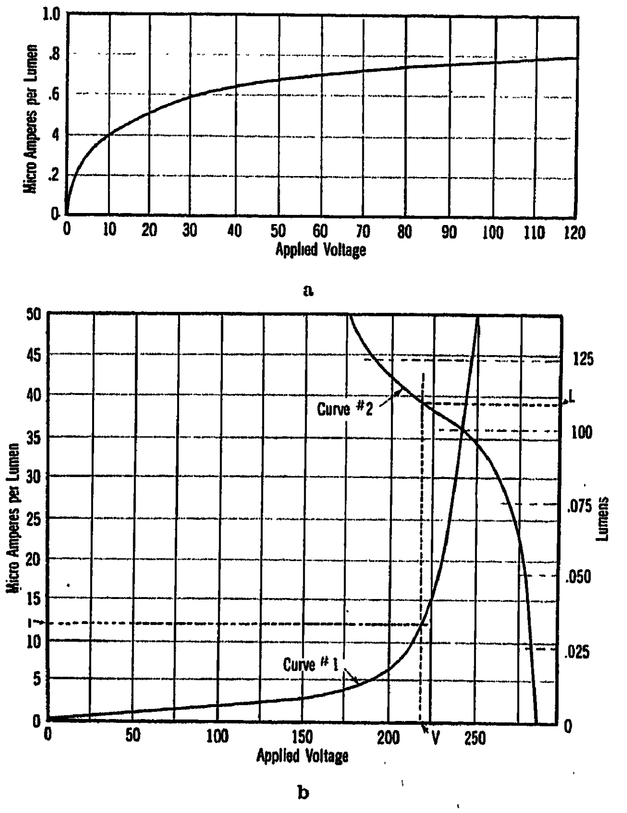

Fig. 4—Curves Showing Photo-Cell Current in Microamperes per Lumen of Light Flux as a Function of Applied Voltage for (a) the High Vacuum and (b,1) the Gas Filled Cell

(Plotted in the above manner the characteristics of the 2½ in. and the 1¼ in. diameter cells are identical). In (b, 2) is shown the illumination limit curve

The photo cells described above are standard. For very special applications cells of special size and shape have been employed. In one instance, that of a sorting unit (described elsewhere), the cells are very small, being cylindrical in shape and 0.5 in. in diameter by 1.75 in. long.

2. Photo-Glow Tube. The photo glow tube developed by D. D. Knowles of the Westinghouse Research Laboratories is a device in principle essentially the same as a gas-filled photoelectric cell with the exception that it is designed to operate at a voltage above what was called the glow point voltage in the case of the photo cell previously described.

The photo glow tube is presented in more detail under the general heading of glow-discharge devices.

3. Selenium Cells. The selenium cell is a form of light sensitive device which functions by reason of the variation in conductivity of the metal selenium with illumination. While the change in conductivity of selenium is considered to be due to the release of photo electrons,[3] the normal construction and operation of such cells is such that they do not fit well into the summary in Table I. To date the selenium cell has not been reduced to the same degree of practicability as have the devices discussed above. Some cells have appeared on the market but they have been very low-voltage cells capable of delivering only small amounts of energy in the output circuit, which energy is insufficient to control sturdy relays. Successive cells of any one type display wide variations in response.

The current output of a selenium cell at constant voltage varies with the square root of the illumination. The speed of response of a selenium cell is considerably slower than that of a photoelectric cell but the current which passes is much greater. However, unless more constant cells are developed, which will make it possible to control sturdy relays without necessitating amplification, their usefulness will be very limited, since with these shortcomings they are inferior to photoelectric cells and amplifiers.

New cells of 110-volt rating able to deliver several watts in the output circuit are under development but as yet they are still a laboratory device.

Glow-Discharge Devices

1. The Two Electrode Glow Tube—Glow Meter Bulb. An example of a glow-discharge tube in its simplest form is the glow meter bulb shown in Fig. 5A. The bulb consists essentially of the two small coiled electrodes sealed into the glass bulb proper, which is filled with neon gas at low pressure. The finished bulb is small, being ½ in. in diameter and about 3½ in. long. Under an impressed voltage of sufficient magnitude the bulb becomes filled with the orange-red neon glow and passes current.

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[3] "Photoelectric Conduction in Selenium," R. J. Piersol, *Phys. Rev.*, 30, November 1927, p. 664.

2. Grid-Glow Tube. The grid controlled glow tube as developed by Knowles[4] consists essentially of a cylindrical aluminum cathode, an anode, and a grid, both of the latter being made of heavy nickel wire. The three electrodes are inclosed in a glass tube containing neon gas at a low pressure. A photograph of the tube is shown in Fig. 6a and a sketch showing the construction is shown in Fig. 6b.

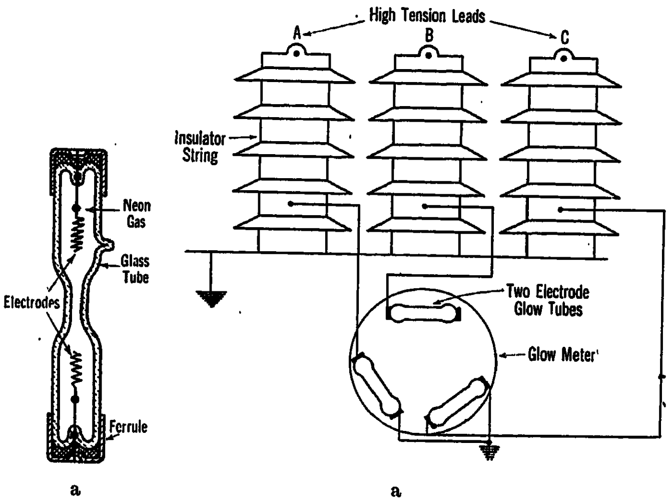

FIG. 5—(a) TWO ELECTRODE GLOW TUBE FOR ELECTRIC STATIC GLOW METER
(b) CONNECTIONS FOR ELECTRIC STATIC GLOW METER WHEN USED AS GROUND DETECTOR

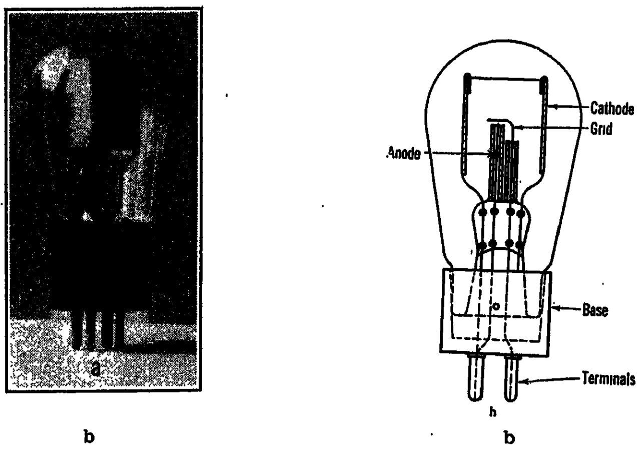

FIG. 6—(a) PHOTOGRAPH OF THE GRID-GLOW TUBE
(b) SKETCH SHOWING DETAILS OF CONSTRUCTION OF THE GRID-GLOW TUBE

The grid-glow tube can be used on both direct and alternating current but, as will be pointed out, its characteristics are somewhat different on the two sources.

The impedance offered to the flow of current from the aluminum cylinder, the cathode, to the central wire, the anode, is practically infinite under all conditions. The impedance offered to the flow of current in the reverse direction is quite low when the tube is glowing, amounting to about 20,000 ohms at 8 milliamperes. The glow resistance is not constant but varies inversely with the current. As a result, the drop over the glow is constant at about 160 volts at all times. To prevent the discharge from passing from a glow to a destructive arc a series resistor must be employed in series with the tube, which should limit the current to about 10 milliamperes (effective).

A unique feature of the grid glow tube is the fact that the voltage required to start the glow is subject to control within wide limits by means of the grid electrode.

A simple circuit for the grid-glow tube is shown in Fig. 7a. If the grid be free (thoroughly insulated) about 600 to 900 volts, d-c., depending on the particular tube in use, will be required to start the glow and operate the relay. This is due to the fact that under free grid conditions the grid will assume a high negative charge, which, if not allowed to leak off, will rise sufficiently to block the tube. The fact that the grid does assume this high negative charge gives rise to one form of control of the breakdown voltage.

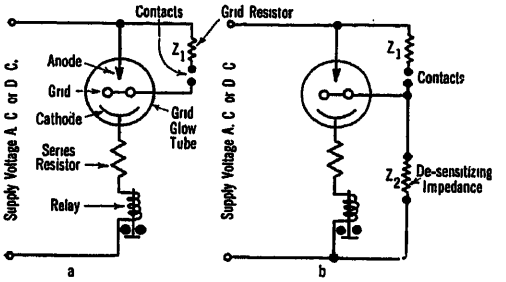

FIG. 7—SCHEMATIC CIRCUIT DIAGRAMS SHOWING BASIC FEATURES INVOLVED IN CONTROL OF THE GRID-GLOW TUBE

In (a) the use of the Grid Resistor functioning as an anode to grid leakage path is shown and in (b) the use of a de-sensitizing impedance is shown

Any conducting path placed in the grid to anode circuit will permit the grid charge to leak off and permit the tube to operate providing the leakage takes place at a sufficiently high rate as demanded by the "threshold" current portion of curve *d* of Fig. 1. The leakage path may be in the form of a condenser, a resistor, or its equivalent; as, for example, a photo cell or a flame. The controlling effect of a grid resistance for alternating current and direct current is shown in Fig. 8.

The amount of energy which must be handled by a pair of control contacts placed in series with the leakage resistor in Fig. 7a, is a very minute quantity. Accordingly it is important that dirt, dust, and moisture be kept out of the tube socket. A good quality socket should be used to avoid leakage in the socket itself. The ratio between the energy controlled in the output of the glow tube and the energy which the above mentioned contacts are called upon to handle is subject to control, and on occasion may be made very high. For instance, if the grid resistance in Fig. 7a is about

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[4] "The Grid-Glow Tube Relay, D. D. Knowles, *The Electric Journal*, April, 1928.

100 megohms, it will be found that a grid current of the order of one microampere will be sufficient to permit the main discharge to start for a certain safe normal anode to cathode voltage. Assuming the relay contacts to be of one ampere capacity, it is seen that the current ratio for this case is of the order of one million to one.

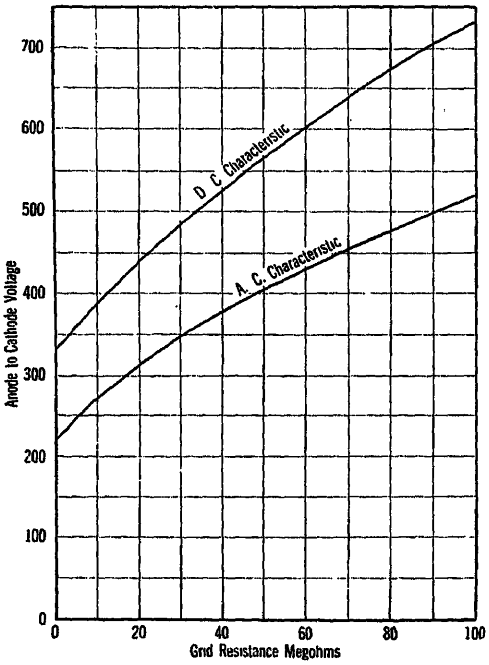

FIG. 8—GRID-GLOW GRID-RESISTANCE CONTROL CHARACTERISTICS FOR A-C. AND D-C. CIRCUITS

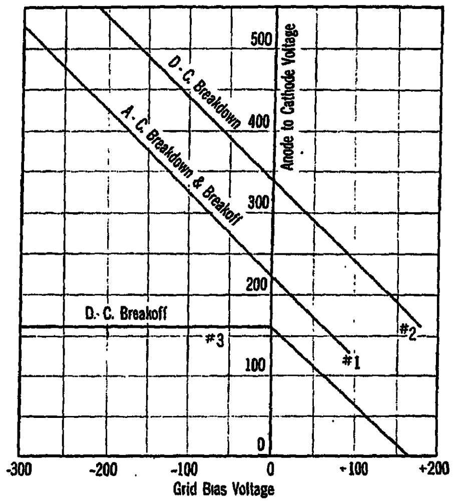

FIG. 9—GRID-GLOW TUBE CURVES SHOWING A-C. AND D-C. ANODE TO CATHODE BREAKDOWN AND BREAK OFF VOLTAGES AS A FUNCTION OF GRID BIAS VOLTAGE.

(Data taken with Zero Grid Resistor in use)

If the sensitivity of such a circuit be thought too great, a means of varying the sensitivity as shown in Fig. 7b can be used. For a given value of voltage between anode and cathode, the ratio between Z_1 and Z_2 will determine whether or not the tube is to break down. The sum of $Z_1 + Z_2$ governs the sensitivity; that is, the energy which is lost in the control circuit. By reducing the sensitivity in this manner the effects of extraneous leakage paths such as socket insulation resistance will be lessened.

If instead of connecting a leakage resistor between anode and grid, an actual voltage is impressed across these points, a second form of control results. Plotting as ordinates the values of the anode to cathode voltage required to cause the tube to glow, and as abscissas the values of the grid to anode voltages, we obtain the "breakdown" curves Nos. 1 and 2 of Fig. 9 for alternating current and direct current respectively. The grid to anode voltage or bias voltage is considered as negative or positive according to whether the grid is negative or positive with respect to the anode at the time the anode is positive with respect to the cathode.

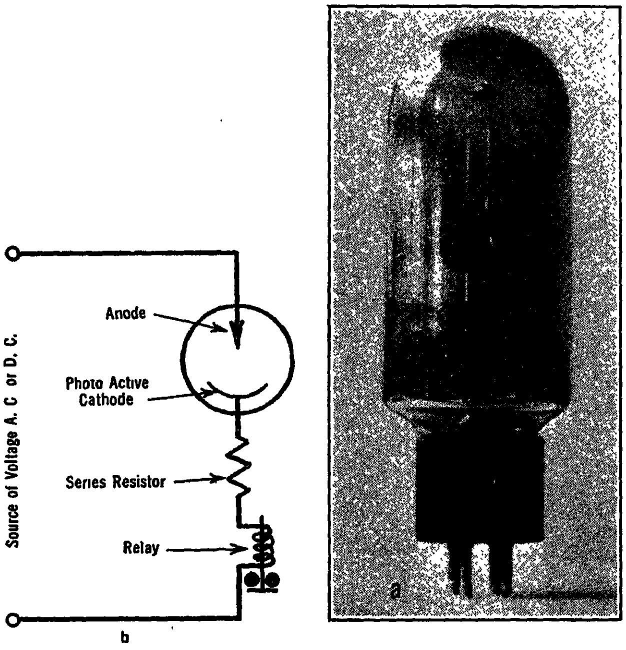

FIG. 10—(a) PHOTOGRAPH OF THE PHOTO-GLOW TUBE
(b) SCHEMATIC CIRCUIT DIAGRAM INVOLVING THE PHOTO-GLOW TUBE

As was mentioned before, the voltage drop over the glow amounts to 160 volts. Accordingly the anode to cathode voltage must be at least 160 volts if the glow is to persist. Curve No. 3 of Fig. 9 shows the "breakoff" curve for d-c. operation. Since on a-c. the voltage wave falls below the 160-volt value in each cycle, the "breakdown" and "breakoff" curves for a-c. operation are seen to coincide.

On direct current, therefore, once the tube has been set in operation by a certain grid influence, it will continue to operate even after the influence has been removed. The glow can be stopped only by reducing the applied anode-cathode voltage below the 160-volt value. On alternating current however, since the breakdown and breakoff curves coincide, the tube will start and stop glowing accordingly as the grid influence is applied or removed.

Advantage may be taken of such characteristics. In the circuit shown in Fig. 16, a glow tube is used to leave a permanent record of the occurrence of a transient in the light supplied to the photo cells. It is functioning in that circuit as an "instantaneous pickup and seal-in" type of relay without contacts.

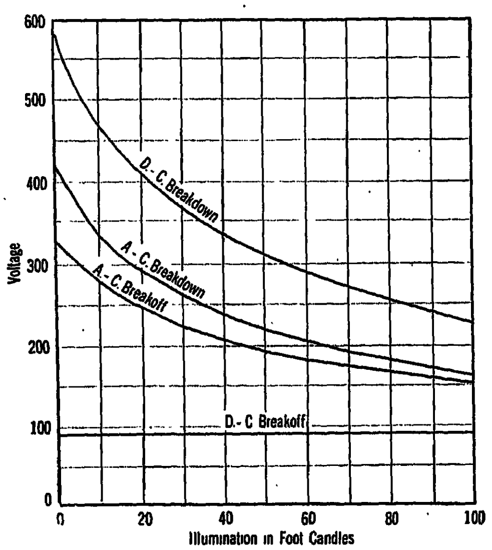

Fig. 11—Curves Showing the A-c. and D-c. Breakdown and Break Off Voltages as a Function of Illumination for the Photo-Glow Tube

Further uses of the grid-glow tube are brought out under the heading of "Applications."

3. Photo-Glow Tube. As mentioned before, the photo glow tube developed by Knowles is a device in principle essentially the same as a gas-filled photoelectric cell, with the exception that it is designed to operate at a voltage above what was called the glow point voltage in the case of the photo cell previously described.

One form of photo glow tube is shown in Fig. 10A. The anode is a centrally located wire having a small area exposed. The cathode, the film of metal deposited upon the inner surface of the glass, serves two functions. The cathode is coated with the photo-active substance and as such serves as a source of electrons when illuminated. Under an impressed voltage of sufficient magnitude, accumulative ionization of the gas with which the tube is filled sets in when the tube is illuminated, and a current will pass, the cathode forming one of the electrodes for the passage of this glow current as well.

Typical performance curves for the photo glow tube are shown in Fig. 11. These curves serve to bring out the fact that the glow, once started, can be made to stop upon a reduction in illumination when the tube is run on alternating current. On direct current however, the glow is self-sustaining and will persist either until the circuit is opened or the applied voltage is reduced below a value corresponding to the value for the constant drop over the glow discharge.

A resistor is normally connected in series with the photo glow tube to limit the glow current to a safe value of 8 milliamperes. A typical circuit diagram for the use of this tube is shown in Fig. 10b.

The response of the photo glow tube is practically instantaneous, and the current which the tube passes is of sufficient magnitude to operate small relays directly, no amplification being necessary.

As developed at the present time, the life of the photo glow tube on continuous duty is not very long. Consequently it should be applied only where the tube is normally not illuminated, and where only an abnormal condition causes breakdown.

Applications

Light Sensitive Devices.

1. Photo Cell Amplifier Unit. The normal current output of the photoelectric cell being of the order of micro-amperes is not readily put to use directly except through the use of very sensitive instruments; it requires that a degree of amplification be given it in order that less sensitive associated apparatus may be employed. A vacuum-tube amplifier may be used for this purpose. One form of such an amplifier is shown in Fig. 12.

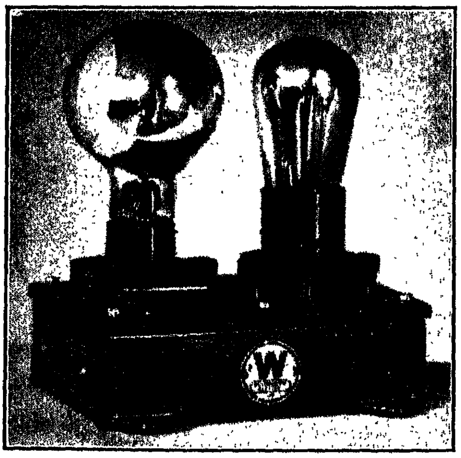

Fig. 12—Illustration Photo-Cell Amplifier Unit Showing a 2½-In. Diameter Photo Cell and a Standard 201-A Radio Tube in Position on the Panel

The internal wiring of the amplifier unit is shown in Fig. 13a. The photo cell and the grid resistor are in series between terminals *A* and *X*. Their common point is run direct to the grid of the amplifier tube. The filament and plate leads to the amplifier tube are run out as shown. Except in special cases, terminals *A* and *P* are connected together, a connecting link being provided for this purpose. The performance of the unit as a whole is evident from an inspection of the typical vacuum tube characteristics as shown in Fig. 13c and the scheme of connection shown in Fig. 13b. Assuming the photo cell is dark, it can be seen that the grid will be at a negative potential with respect to the filament as determined almost solely by the value of the C battery. If the photo cell be illuminated, a current will flow under the influence of the B and C batteries combined, from the positive terminal of the B battery through the photo cell, and will then return to the negative terminal of the C battery after passing through the grid resistor, across which, as a result, there will exist a difference of potential. The polarity of this voltage drop over the grid resistor will be such as to tend to cause the grid to become positive with respect to the filament: in other words, the effective negative grid bias will have been reduced. From Fig. 13c, it can be seen that this reduction in bias voltage will result in an increased flow of plate current, and as a result the relay in the plate circuit will be energized.

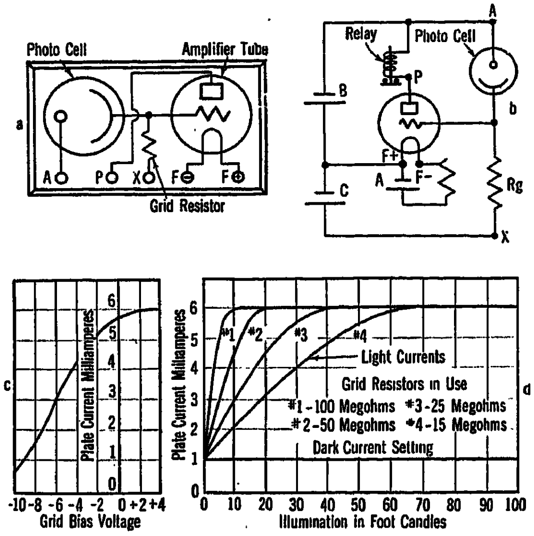

FIG. 13—(a) INTERNAL WIRING DIAGRAM OF THE PHOTO-CELL AMPLIFIER UNIT

(b) SCHEMATIC DIAGRAM SHOWING SIMPLE CIRCUIT FOR USE WITH PHOTO-CELL AMPLIFIER UNIT

(c) TYPICAL DYNAMIC PLATE CURRENT—GRID BIAS CHARACTERISTIC FOR AN AMPLIFIER TUBE

(d) TYPICAL CURVES SHOWING THE AMPLIFIER PLATE CURRENT AS A FUNCTION OF ILLUMINATION ON THE PHOTO CELL FOR VARIOUS VALUES OF THE GRID RESISTOR

Assuming an initial bias voltage of 9 volts, and assuming a 50-megohm grid resistor in use, it is seen from Fig. 13c, that upon illuminating the photo cell slightly, if 0.06 micro-ampere should flow, the voltage drop over the grid resistor would amount to 6 volts and the plate current would rise from one milliampere to three milliamperes. From the typical curve in Fig. 13d, for a 50-megohm grid resistor, it is seen that an illumination intensity of about 5 foot-candles should produce this result.

The unit responds very quickly to changes in illumination. The time lag is generally of the order of 0.001 to 0.0001 second. This figure is for the plate current in the vacuum tube. When a relay is used an additional time lag enters, depending on the speed with which the moving armature picks up and closes its contacts.

Typical curves showing milliamperes plate current as a function of cell illumination for various grid resistors in use are shown in Fig. 13d. By the proper choice of grid resistor, amplifier tube, and circuit voltage, the region of the curve wherein plate current is proportional to the illumination can be made to cover either wide or narrow ranges of illumination intensities to suit any particular requirements.

Since both the photoelectric cell and the amplifier tube are inherently rectifiers, the entire circuit can be operated on alternating current. In this case it is customary to shunt the relay, shown in the plate circuit of the amplifier tube, with a condenser to minimize the effect of the ripple. Circuits have been developed that lend themselves particularly to alternating current operation.

By means of a special circuit the photo cell can be made to bring about a reduction instead of an increase in the amplifier tube plate current upon being illuminated. This modification is incorporated in the circuit shown in Fig. 21. The modification in addition to bringing about the above mentioned reversed amplifying effect provides a satisfactory means of compensation for changes in line voltage which would otherwise seriously affect the constancy of the calibration of the amplifier unit.

The grid resistor used as a coupling resistor between the photoelectric cell and the amplifier tube is of the "thin-film" type shown in Fig. 14. The resistance proper is made up of a small helix of glass coated with a thin film of metal evaporated in the process of construction, from the concentrically located molybdenum filament. The filament is used only in the construction of the thin resistance film.

Other types of grid resistors are used for special requirements.

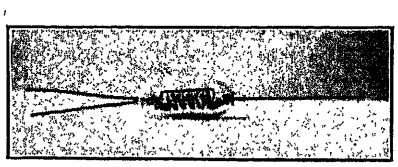

FIG. 14—THE THIN METAL FILM TYPE OF GRID RESISTOR USED IN THE PHOTO-CELL AMPLIFIER UNITS

2. *Multi-Cell Circuit.* An extremely useful modification of the simple photoelectric cell amplifier circuit of Fig. 13b, is the multi-cell arrangement shown in Fig. 15.

For a given voltage impressed across the series circuit composed of the cells and the grid resistor, the voltage drop over the resistor and the voltage per cell depends upon the number of cells, the illumination, and the current-voltage curve for each cell. For uniform illumination and for identical cells the voltage per cell will be the same.

The cells generally used in such series arrangements are of the high vacuum type. By reason of the pronounced saturation effect of such cells the response of the series of cells to a reduction in the illumination on one cell only, as is manifested by a reduction in voltage drop over the grid resistor and a consequent reduction in amplifier tube plate current, is almost as pronounced as it is for a reduction of like amount in the illumination supplied to all of the cells of the series. In other words, the partial darkening of one cell of the series is very nearly equivalent to a partial darkening (to the same extent) of all of the cells of the series.

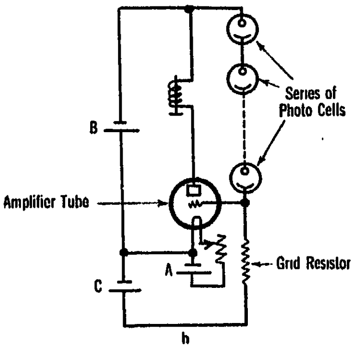

Fig. 15—Single Stage Multi-Cell Circuit for Amplification of Photo-Cell Currents Derived from a Group of Photo Cells Connected in Series

The response afforded by the single-stage circuit can of course be increased through the use of additional stages of vacuum tube amplification. A circuit showing such an arrangement is presented in Fig. 16. The details of this circuit are further taken up under the topic "Sorting of Materials."

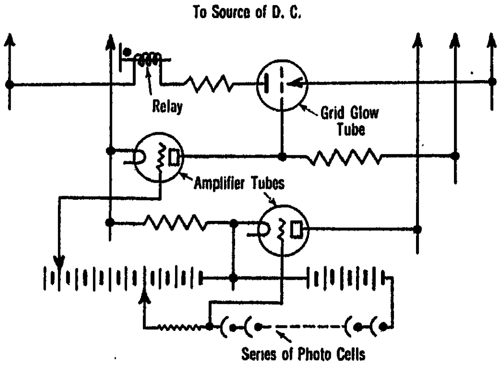

Fig. 16—One Form of Two Stage D-c. Amplification of Photo-Cell Currents. The Grid-Glow Tube is Shown in this Circuit Functioning as an Instantaneous "Pick-up and Seal-In" Type of Relay without Contacts

3. Sorting of Materials. Fig. 17 shows in schematic form the essential elements involved in the photoelectric examination of surfaces of materials. Light is supplied by the concentrated filament lamp and is brought to a focus at the surface under examination. The amount of light which the photo cell receives by reflection is dependent upon the reflection coefficient for the particular portion of the surface illuminated.

Any discontinuity or irregularity in the surface under examination which results in a variation from normal in the light flux supplied to the photo cell is made evident by the amplifier circuits which are connected to the photo cell.

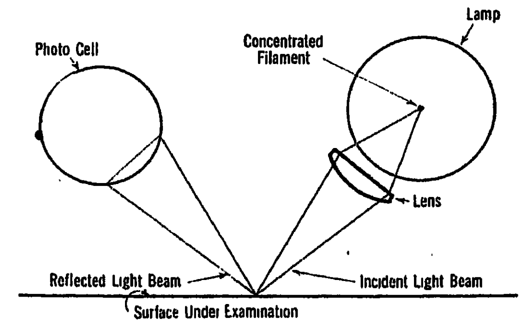

Fig. 17—Sketch Showing the Essential Elements Involved in the Application of a Photo Cell to the Examination and Sorting of Opaque Materials

Obviously the actual area under examination is quite limited when a single photoelectric cell is used. The multi-cell arrangement discussed previously lends itself very well to the examination of more extended surfaces where it is desired to pick out irregularities extending over relatively small parts of the surface.

A photograph of a multi-cell unit employing special cells of only ½-in. diameter is shown in Fig. 18. This particular unit incorporates all of the essentials pointed out in Fig. 17. The light is supplied by a special straight-line filament lamp and is brought to a straight line focus on the surface under examination by means of a cylindrical lens. The material under examination can be made to travel automatically in a direction at right angles to the line of light focused on the surface. Associated apparatus can be employed so that surface

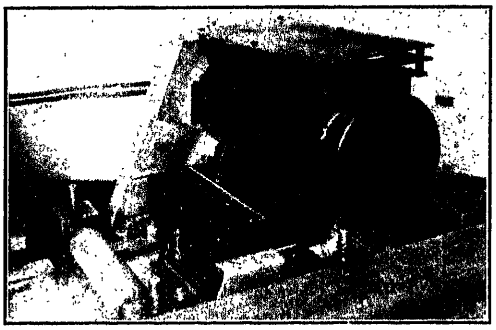

Fig. 18—Photograph Showing a Housing Built to Accommodate a Special Straight Line Filament Lamp, a Cylindrical Condensing Lens, and a Series Connected Group of Special One-Half Inch Diameter Photo Cells. The Unit is an Experimental Model Used in a Photoelectric Sorting Application

irregularities of a certain magnitude will cause automatic separation of perfect from imperfect material. One of the amplifying circuits associated with this unit is the one mentioned before and presented in its elementary form in Fig. 16. In this particular circuit, advantage is taken of the d-c. seal-in characteristics of the grid-glow tube, with the result that even if the above mentioned surface irregularity be of very short duration, the output of the control circuit is left permanently affected by the passage of the irregularity. This gives time for relatively slow moving relays to act, and for mechanical movements to take place in the associated automatic sorting machinery. Fig. 19 shows an assembled amplifier unit.

4. Color Measurements and Sorting. The single photoelectric cell and amplifier as represented by the photo cell amplifier unit of Fig. 12 can be used in conjunction with color filters to aid in matching the colors of materials.

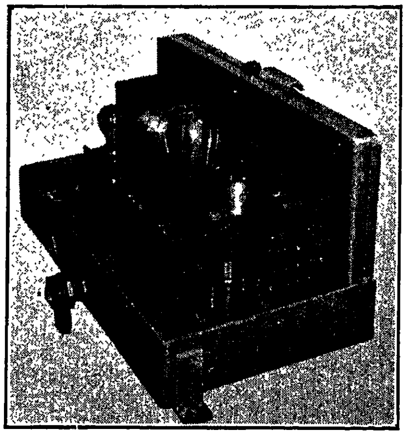

Fig. 19—Photograph Showing the Amplifier Unit Used with the Unit Shown in Fig. 18. This Amplifier Makes Use of the Grid-Glow Tube in the Manner Shown in Fig. 16

By substituting a second photoelectric cell for the grid resistor $R g$ in Fig. 13B and by illuminating the two photo cells by light reflected from the surface or surfaces under examination, a difference in the reflection coefficients of the materials can within limits be detected regardless of the absolute value of those coefficients.

5. Photoelectric Smoke Recorder. A photoelectric smoke recorder has been developed for power plants for the purpose of recording the smoke density in the smoke stack.

While the plant operator has had available instruments such as the CO_2 meter and the boiler meter, which instruments assist in operating the boilers efficiently, there has been no device available which would give him a true indication of smoke. For this reason, methods like the Ringelman's Chart had to be resorted to. Evidently, any visual method that depends on watching the smoke issuing from the stack, is very approximate, as it depends upon the eye of the operator, and is entirely useless at night. Since smoke abatement is a subject that receives more and more attention, as is evidenced by smoke ordinances in all large cities, the photoelectric smoke detector should find a valuable field.

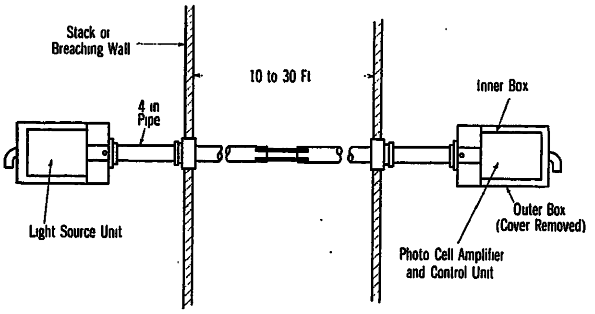

Fig. 21—Photoelectric Smoke Recorder Installation for Measuring Smoke Density in Smoke Stack

Fig. 20 shows a sketch of an outdoor installation and Fig. 21 a diagram of the circuit. A pipe extends through the breaching or stack on one end of which is mounted a light source and lens. On the other end is located the photoelectric cell and amplifier unit, similar to that shown in Fig. 12 plus other control equipment. In the boiler room is located the indicating or recording meter, calibrated in degrees of smoke, as well as an alarm which rings whenever the smoke density reaches a predetermined amount.

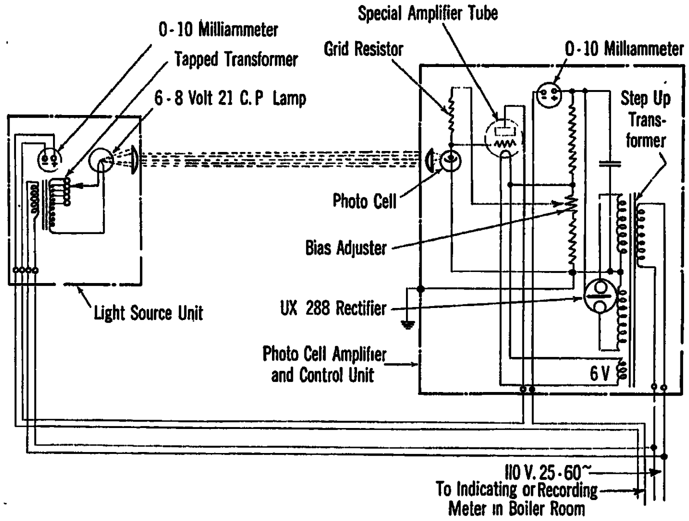

Fig. 21—Circuit Diagram of Photoelectric Smoke Recorder

The device operates entirely from the available a-c. supply, the light source and vacuum tube being operated at a rating that insures long life and the device being compensated for voltage variations of the supply source. The light source unit and the receiving unit are of weatherproof construction. They are so designed that no smoke or dirt can settle on the lenses, photo cell, or light source.

Among other applications of this device, an important one might be in the mining industry in connection with high-voltage ore dust precipitators, for indicating or recording the efficiency and operativeness of the precipitators.

6. *Photoelectric Smoke Detector.* This device is similar to the smoke recorder except that it is simplified mechanically. It consists of two units, the light source and the photo cell amplifier unit, photographs of which are shown respectively in parts *a* and *b* of Fig. 22. The circuit diagram is similar to that of the smoke recorder shown in Fig. 21. Both the light source and the photo cell amplifier unit are operated directly from alternating current.

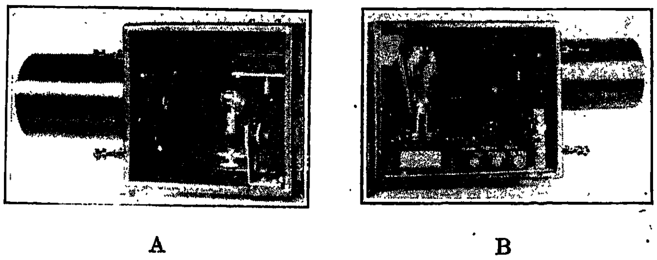

Fig. 22—Photoelectric Smoke Detector

a. Light source unit
b. Photo-cell amplifier and control unit

Whenever smoke interrupts the beam of light or cuts off part of the light, a relay in the amplifier circuit operates. An important application of this device is in connection with fire extinguishing apparatus such as CO_2 equipments. It can be used for protection of electrical machinery such as generators, as shown in Fig. 23, and in many industrial fields, particularly where a fire is apt to spread quickly and cause damage in a short time, as in dipping tanks, lacquer spray booths, etc. So far thermostats have been used for automatically releasing the extinguishing equipment, but these thermostats are inherently slow.

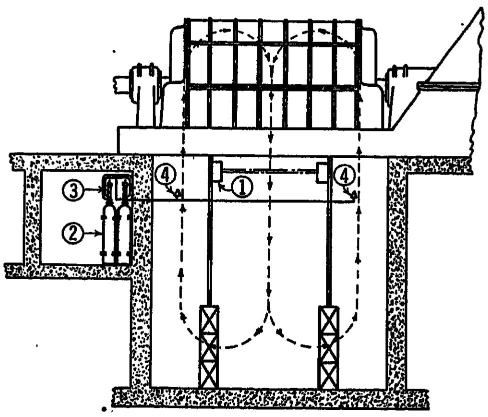

Fig. 23—Application of Photoelectric Smoke Detector to Generator Protection

1. Smoke detector
2. Carbon dioxide cylinders
3. Electric-automatic-manual head
4. Discharge

Many other uses suggest themselves for this device, such as for counting and timing operations. An interesting application is that of a photoelectric flag switch in steel mills, suitable for starting shears when rolling light flat material. Various types of mechanical switches have been used to start the shears which cut up the material into definite lengths while the material is still in motion, but they do not stand up under severe service conditions. A light sensitive device obviates these difficulties.

7. *Photo-Glow Tube Unit.* A photograph of a photo glow tube unit is shown in Fig. 24. The circuit is similar to that shown in Fig. 10b, the source of voltage being 110 volts a-c. stepped up through a transformer having secondary taps for adjustments. As mentioned before, photo glow tubes have not been developed to a stage where they have a long life when the glow discharge passes continuously. However, if they are normally deenergized and have to function at more or less infrequent intervals, their life is very satisfactory. On account of the simplicity of such a unit it is to be preferred over the photoelectric cell unit described previously.

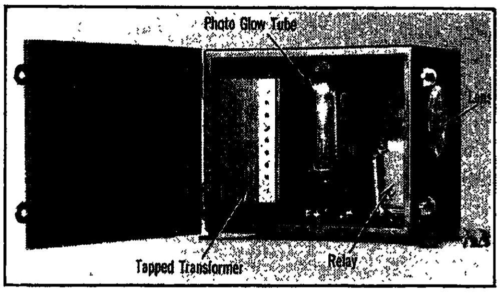

Fig. 24—Photo Glow-Tube Unit for Use as a Smoke Detector, Flash Detector, Etc.

One important application of this device is as a flash detector, in connection with the protection of oil circuit breakers, bus bar structures, etc. In this manner, fire extinguishing means can be released instantly upon the occurrence of a severe flash in a circuit breaker in order to prevent the spreading of an oil fire.

Another application is shown in Fig. 25. The device shown is an experimental unit and not the commercial device. It is used as a paper break recorder on a paper machine, and is installed both on the dry end as well as on the wet end of the machine. Whenever a break occurs, an alarm is sounded so that no time is lost in starting the paper going again. Also, a record is made on a recording meter to indicate the location of the break, the time of the occurrence, and its duration.

Glow Devices

1. *Electrostatic Glow Meter.* One of the simplest applications of a glow discharge device is the Electrostatic Glow Meter. The three-phase glow meter consists of three small two electrode glow discharge

tubes of the type shown in Fig. 5a, suitably mounted and connected as indicated in Fig. 5b. By the use of a set of insulators functioning as a condenser-potentiometer, a voltage is impressed on each tube, which is proportional to the voltage between line conductor and ground. Normally, the three tubes give out a bright orange-red glow which is characteristic of the neon gas with which they are filled. A grounded conductor is indicated by a darkened tube.

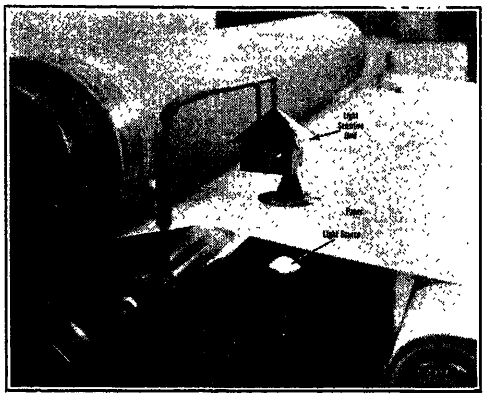

Fig. 25—Experimental Installation of a Paper Break Recorder on a Paper Machine

The electrostatic glow meter is especially applicable at high tension switching stations because of the fact that potential transformers are not needed. The insulator string potentiometer provides an adequate energy supply for the device.

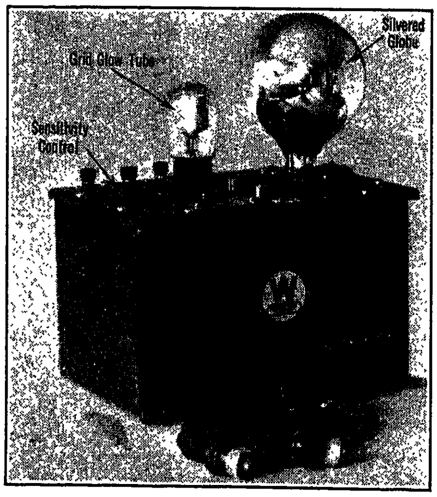

Fig. 26—Grid-Glow Tube Demonstration Set

2. Grid-Glow Tube Used with Contact Making Instrument. A means for controlling the action of a grid glow tube by means of a contact making instrument is afforded by the arrangement in Fig. 7b. As mentioned previously, the circuit constants can be so arranged that the active contacts are called upon to handle currents of very small magnitude. In the instance previously given, a one-ampere load was controlled with a contact load of only one microampere. When operated on alternating current the contacts can be placed in series with Z_2 instead of in series with Z_1 if it is desired that the glow tube become deenergized upon closing the contacts.

3. Grid-Glow Tube Demonstration Set. The grid-glow tube demonstration set pictured in Fig. 26 is a device which takes advantage of the condenser potentiometer form of control of the grid-glow tube. The impedance Z_2 in Fig. 7b takes the form of a variable condenser, which provides a control on the sensitivity. The impedance Z_1 is accounted for in the capacity between the operator's hand and the silvered globe.

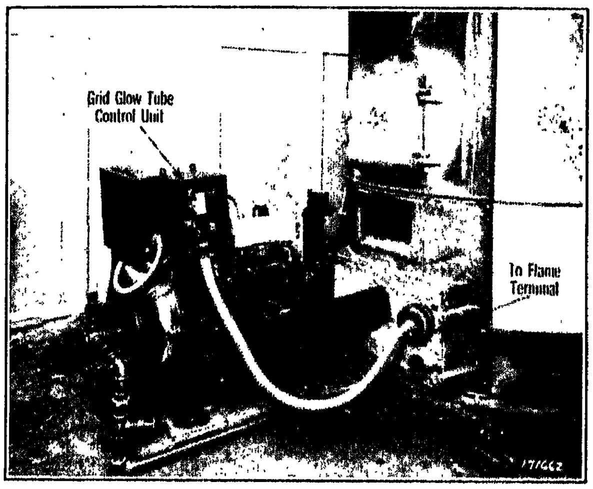

Fig. 27—Domestic Oil Burner Installation, Using Grid-Glow Tube Control Unit and Flame Terminal

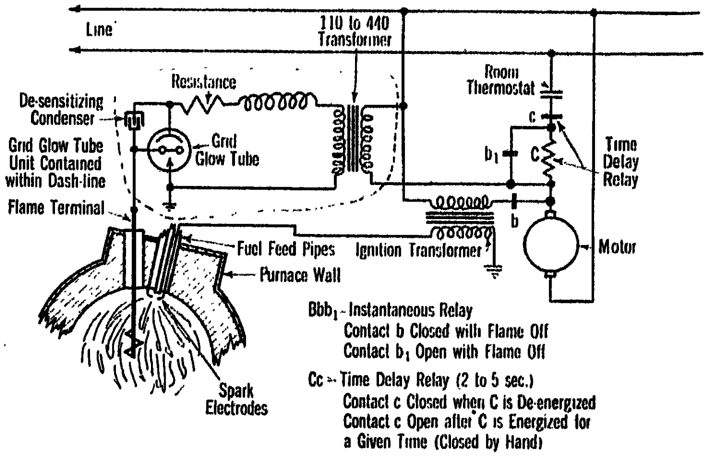
Line
110 to 440 Transformer
Resistance
De-sensitizing Condenser
Grid Glow Tube Unit Contained within Dash-line
Grid Glow Tube
Flame Terminal
Room Thermostat
c
b_1
C
Time Delay Relay
b
Motor
Fuel Feed Pipes
Ignition Transformer
Furnace Wall
Spark Electrodes
Bbb_1 - Instantaneous Relay
Contact b Closed with Flame Off
Contact b_1 Open with Flame Off
Cc - Time Delay Relay (2 to 5 sec.)
Contact c Closed when C is De-energized
Contact c Open after C is Energized for a Given Time (Closed by Hand)

Fig. 28—Circuit Diagram of Domestic Oil Burner Control, Using Grid-Glow Tube Unit as a Combustion Safety Device

The device serves as a novel means for controlling moving displays in shop windows. When the demonstration set is properly installed and adjusted, it is only necessary for the onlooker to bring his open hand up to within an inch from the surface of the silvered globe, the glow tube being caused to glow and thereby energizing the relay which forms a part of the set. Through the circuits set up by the relay contacts, the various displays are thus brought into motion.

Means are provided so that a small metal foil disk attached to the inside surface of a window may be connected to the set so as to function in place of the silvered globe. A passerby need only bring the palm of his hand up to the outside surface of the window near the metal disk to start the set and actuate the display.

4. Grid-Glow Tube Oil Burner Control. A domestic oil burner installation, using a grid-glow tube combustion safety device, is shown in Fig. 27, and a diagram of the complete automatic control is shown in Fig. 28.

Until now, thermostatic devices, operated by the heat of the flame and located in the flue or in proximity to the fire brick of the furnace, have been used as a safety device, to prevent puff backs or more serious explosions in case of (a) belated electric ignition in starting the burner, (b) flame failure while the burner is operating. These puff backs occur if belated ignition takes place after a certain amount of atomized oil has been introduced into the furnace, about 5 sec. being sufficient to cause such trouble. Since these thermostatic devices take from 5 to 90 sec. to operate, depending on operating conditions, unsafe conditions result.

The grid-glow tube does not operate on the heat of the flame, but on its conductivity, the conductivity being zero with no flame. This conductivity is measured between a flame terminal and ground, if the flame or the conducting gases reach the grounded metallic furnace structure (see Fig. 28), or between two flame terminals. The description of the resistance control of the grid glow tube as given in the paragraphs relating to Fig. 8 under Part 2 of Glow Discharge Devices will serve as an explanation of the theory of operation.

The action of the grid-glow tube is instantaneous, and the relay *C*, Fig. 28, introduces a time delay of 2 to 3 seconds before shutting down the motor in case of flame failure. This time delay is necessary so as to allow sufficient time under normal condition for the fuel to reach the furnace after the starting of the motor.

Brief reference has been made in this paper to the initiative of our Research Department and interested research engineers in the development of the devices described in this paper, which is really a basis on which the art rests. The authors also wish to acknowledge the important work rendered by Dr. V. Zworykin, Mr. D. D. Knowles, and Mr. L. Sutherlin, as well as the Research Department as a whole, in the development of the applications and complete apparatus described in this paper.

CONCLUSIONS

On account of the wide scope of the subject discussed in this paper, it was not possible to cover the theory nor the applications of these devices in as much detail as might be desirable. However, it is intended to discuss several of the topics in this paper more specifically in other publications.

It is hoped that this article will act as a stimulus toward a broader recognition of the possibilities of tube devices in the industry, and that it will bring forth valuable suggestions which will result in other important applications.

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